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* Black Body :

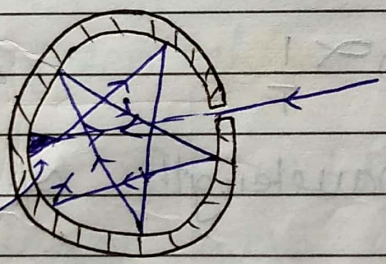
A Body which absorve all incident radiation irrespectevly of frequency and wave length completely.

A Lamp black surface is near black but not perfectly black because it absorve visible light, infera-red radiations but not far infra-red radiations.

A Black body is perfectly absorver as well as emitter.

* Realization of a black body in practice :

Fevry :



Cannonical Projection.

- Small opening and hole on the surface on the hollow on surface sphere act as a Black Body.

- When the Black Body is heated the emitted all the possible radiations.

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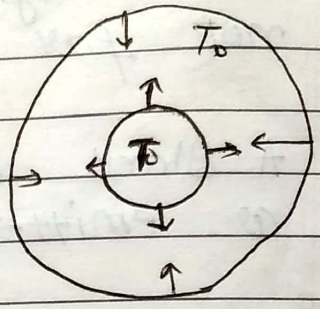
* **Stefan's Law :**

$$E \propto T^4$$

$$E = \sigma T^4$$

According to stefan's Law Amount of radiate energy emitted per unit time per unit Area is directly Proportional to Fourth Power of its absolute temp.

then $E = \sigma(T^4 - T_0^4)$

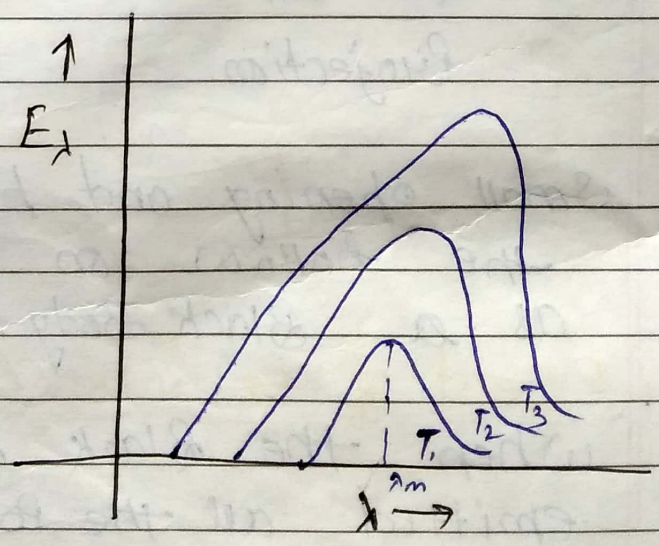


* **Wean's Displacement Law :**

$$\lambda_m \propto \frac{1}{T} \qquad \lambda_m \cdot T = \text{Constant}$$

$\lambda_m \Rightarrow$ wavelength of maximum radiating.

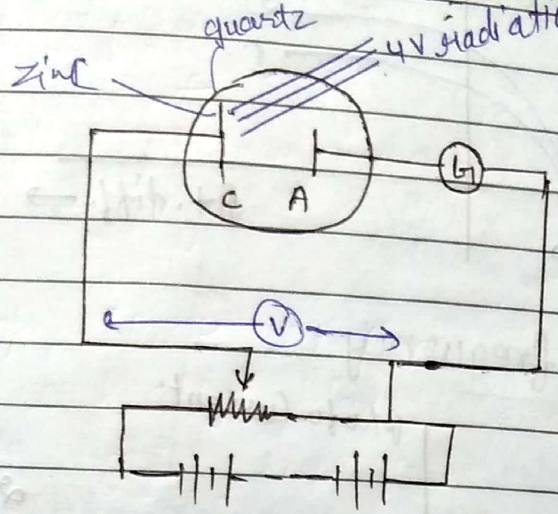
$T_3 > T_2 > T_1$



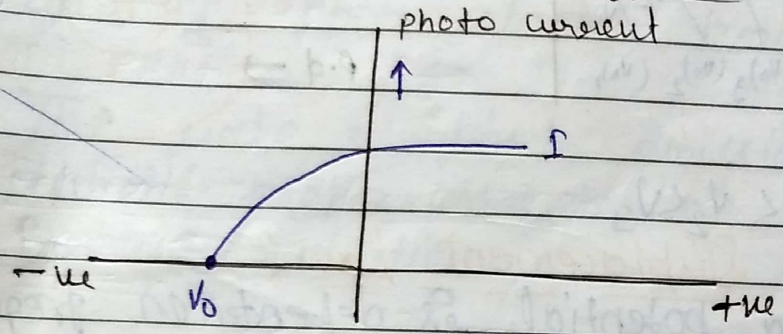
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Photo electric emission:



(i) Effect of potential difference:



V_0 → Stopping potential.

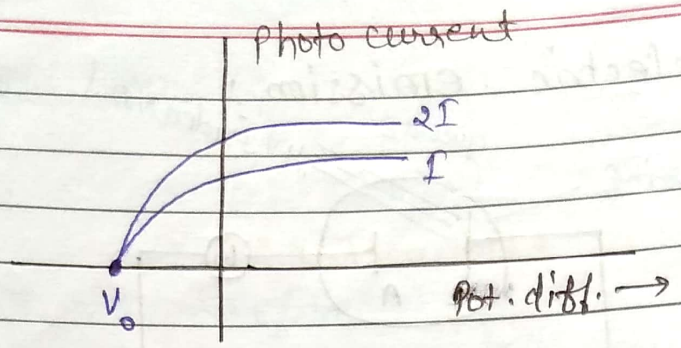
- Retarding potential for which photo electric current just become zero called Stopping Potential.

K.E of emitting = eV_0

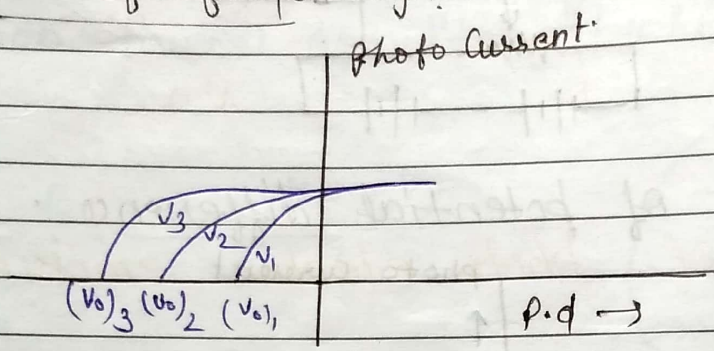
$$\frac{1}{2}mv^2 = eV_0$$

(ii) Effect of intensity:

The no. of photo electron ejected from photo sensetive plate is proportional to Intensity of the incident light.



(iii) Effect of frequency:

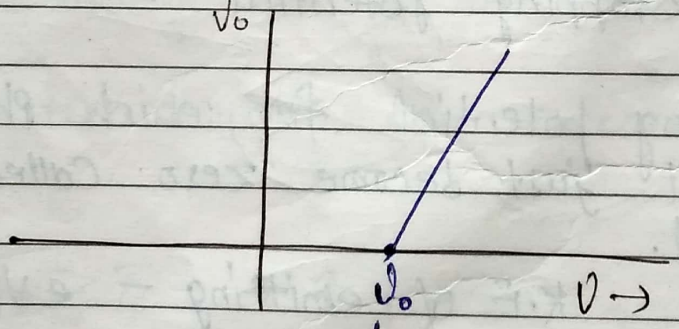


$\frac{1}{2}mv^2 = eV_0$

$K\varepsilon = h\upsilon$

$\upsilon_1 < \upsilon_2 < \upsilon_3$

Stopping potential is dependent on frequency.



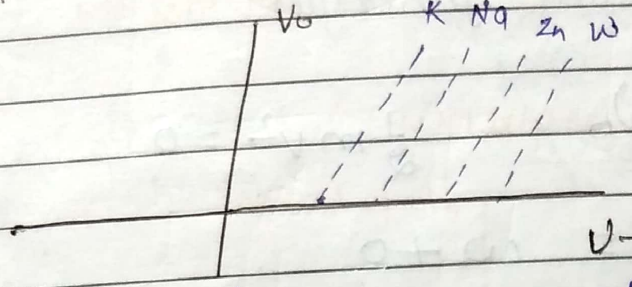
↳ Threshold frequency.

- Threshold frequency: Minimum value of frequency of incident light below which the photo electric emission stop completely. However the intensity of light may be called threshold frequency

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Threshold frequency is the characteristic of photometal.

(iv) Effect of photometal :-



ν_0 → depends on nature of photo metal.

* Laws of photo electric emission :-

(1) The rate of photo emission is directly proportional to the frequency of incident radiation.

(2) The K.E of emitted photo electron electron is independent of intensity and directly proportional to the frequency of the incident radiations.

(3) The Photo emission take place only above a certain frequency known as threshold frequency. This frequency is characteristic freq. of photo metal used.

(4) There is no time lag between incident of radiation and emission of photo electron.

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* Einstien theory of photo electric effect :

$$h\nu = \omega + \frac{1}{2}mv^2$$

ω = work function

at $\nu = \nu_0$, $\frac{1}{2}mv^2 = 0$

$$h\nu_0 = \omega + 0$$

$$\omega = h\nu_0$$

$$h\nu = h\nu_0 + \frac{1}{2}mv^2$$

$$\boxed{\frac{1}{2}mv^2 = h\nu - h\nu_0}$$

if $\nu < \nu_0$

$$h\nu < h\nu_0$$

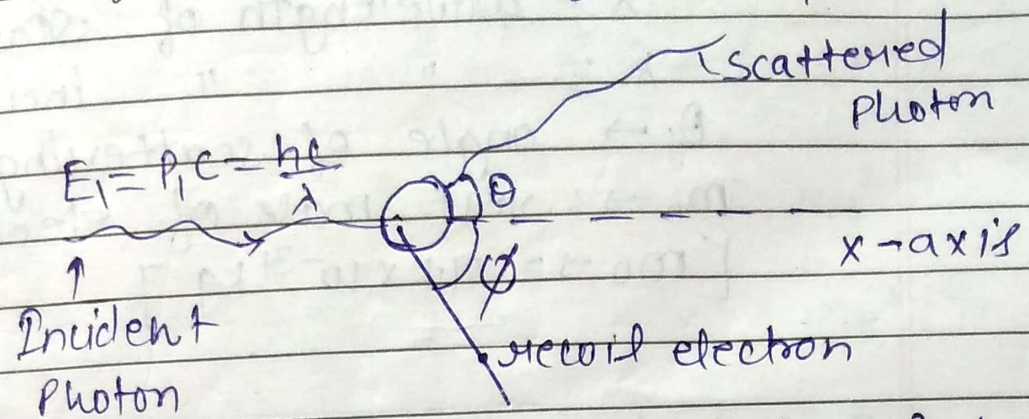
$$\frac{1}{2}mv^2 = h\nu - h\nu_0$$

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Imp.

* Compton effect :-



$$E^2 = P_e^2 c^2 + m_0^2 c^4$$

$$P_1 = \frac{h}{\lambda}, \quad P_2 = \frac{h}{\lambda'}$$

$E \Rightarrow$ Total relativistic energy of electron

$E^2 = P^2c^2 + m_0^2c^4$

$E_0 = m_0c^2 \rightarrow$ rest mass energy

$E_K = (m - m_0)c^2 \rightarrow$ K.E of $e^{\ominus}$

→ when high energy ~~pot~~ Photon ($E > 0.5$ Mev) is incident on a metal then the scattered photon contain not only the wavelength of incident photon but higher then the wavelength of incident photon. This phenomina is known as compton effect.

and the change in wave length is known as compton shift. it is denoted by $\Delta\lambda$

$$\Delta\lambda = \lambda' - \lambda = \frac{h}{m_0 c}[1 - \cos\theta]$$

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where

λ' = wavelength of scattered photon
λ = " " incident photon
$\theta \rightarrow$ angle of scattering
$m_0 \rightarrow$ rest mass of electron
$[m_0 = 9.1 \times 10^{-31} kg]$

For derivation

Apply the Conservation Law of E & P

Applied conservation of momentum (P)

Along x axis :

$$P_1 + 0 = P_2 \cos\theta + P_e \cos\phi$$
$$P_1 - P_2 \cos\theta = P_e \cos\phi \quad --- (a)$$

Along Y axis :

$$0 + 0 = P_2 \sin\theta - P_e \sin\phi$$
$$P_2 \sin\theta = P_e \sin\phi \quad --- (b)$$

By squaring and adding eq^n (a) and (b)

$$(P_1 - P_2\cos\theta)^2 + P_2^2 \sin^2\theta = P_e^2 (\cos^2\phi + \sin^2\phi)$$
$$P_1^2 + P_2^2 \cos^2\theta - 2P_1P_2\cos\theta + P_2^2 \sin^2\theta = P_e^2$$
$$P_1^2 + P_2^2 - 2P_1P_2\cos\theta = P_e^2 \quad --- (1)$$

P_2C

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by Appling conservation of Energy

$$P_1c + m_0c^2 = P_2c + \sqrt{P_e^2c^2 + m_0^2c^4}$$

$$(P_1c - P_2c) + m_0c^2 = \sqrt{P_e^2c^2 + m_0^2c^4}$$

$$\left((P_1 - P_2)c + m_0c^2\right)^2 = P_e^2c^2 + m_0^2c^4$$

$$(P_1 - P_2)^2c^2 + m_0^2c^4 + 2(P_1 - P_2)m_0c^3 = P_e^2c^2 + m_0^2c^4$$

$$(P_1 - P_2)^2 + 2(P_1 - P_2)m_0c = P_e^2$$

$$P_1^2 + P_2^2 + 2P_1P_2 + 2(P_1 - P_2)m_0c = P_e^2 \quad -(2)$$

by equating eq^n (1) and (2)

$$P_1^2 + P_2^2 + 2P_1P_2 + 2(P_1 - P_2)m_0c = P_1^2 + P_2^2 - 2P_1P_2\cos\theta$$

$$P_1P_2(1 - \cos\theta) = (P_1 - P_2)m_0c \quad (3)$$

$$P_1 = \frac{h}{\lambda} \qquad P_2 = \frac{h}{\lambda'}$$

$$\frac{hh}{\lambda\lambda'}[1 - \cos\theta] = h\left(\frac{\lambda' - \lambda}{\lambda\lambda'}\right)m_0c$$

$$\lambda' - \lambda = \frac{h}{m_0c}(1 - \cos\theta).$$

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Conclusions :

(i) Compton ~~shift~~ depends on angle of ~~staining~~ scattering of photon.

if $\theta = 0$

$\Delta\lambda = \lambda' - \lambda = 0$

$\lambda' = \lambda$

there is no scattering along the direction of incident photon.

Dub

(ii) when $\theta = 90°$

$$\Delta\lambda = \lambda' - \lambda = \frac{h}{m_0 c}[1 - \cos 90°]$$

$$\lambda' - \lambda = \frac{h}{m_0 c} = \frac{6.63 \times 10^{-34}}{9.1 \times 10^{-31} \times 3 \times 10^{8}}$$

$$\boxed{\Delta\lambda = \lambda' - \lambda = 0.0243\ A°}$$

↓ Compton wavelength → λ_c

$$\lambda_c = 0.0243\ A°$$

Dub.

(iii) when $\theta = 180°$

$$\Delta\lambda_{max} = \lambda' - \lambda = \frac{2h}{m_0 c}$$

$$\boxed{\Delta\lambda_{max} = 0.0486\ A°}$$

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* Direction of Recoil electron : (ϕ) ⇒

By using eq^n (a) and (b)

$$P_1 - P_2\cos\theta = P_e\cos\phi \quad - (a)$$
$$P_2\sin\theta = P_e\sin\phi \quad - (b)$$

divide eq^n (b) by (a)

$$\tan\phi = \frac{P_2\sin\theta}{P_1 - P_2\cos\theta} = \frac{\frac{h}{\lambda'}\sin\theta}{\frac{h}{\lambda} - \frac{h}{\lambda}\cos\theta}$$

$$\boxed{\tan\phi = \frac{\lambda\sin\theta}{\lambda' - \lambda\cos\theta}}$$

$$\lambda' - \lambda = \frac{h}{m_0c}(1 - \cos\theta)$$

$$\lambda' - \lambda = \frac{2h}{m_0c}\sin^2\theta/2$$

$$\tan\phi = \frac{2\lambda\sin\theta/2\cos\theta/2}{\lambda + \frac{2h}{m_0c}\sin^2\theta/2 - \lambda(1 - 2\sin^2\theta/2)}$$

$$= \frac{\lambda\sin\theta/2\cos\theta/2}{\left(\frac{h}{m_0c} + \lambda\right)\sin^2\theta/2}$$

$$\boxed{\tan\phi = \frac{\lambda\cot\theta/2}{\lambda + \frac{h}{m_0c}}}$$

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T- Problems

Q.1 X-Rays of wavelength $0.10\,A^\circ$ are scattered from a target.

(i) Find the wavelength of x-ray scattered through 45°

(ii) Find the max wavelength present in the scattered x-Rays.

(iii) Find the max. KE of the recoil $e^\ominus$

Soln: Given: $\lambda = 0.10\,A^\circ$

$\theta = 45^\circ$

(a)

$$\Delta\lambda = \lambda' - \lambda = \frac{h}{m_0 c}(1-\cos\theta)$$

$$\lambda' = 0.0243 \times 10^{-10}(1-\cos 45^\circ) + 0.10\,A^\circ$$

$$\lambda' = 0.0243 \times 10^{-10}\left(1-\frac{1}{\sqrt{2}}\right) + 0.10\,A^\circ$$

$$\lambda' = 0.0243 \times 0.414 \times 10^{-10} + 0.10 \times 10^{-10}$$

$$\lambda' = 0.107\,A^\circ$$

(ii) $\lambda'_{max} = \lambda' - \lambda = \frac{h}{m_0 c}(1-\cos\theta)$ (at $\theta = 180^\circ$)

$$\lambda'_{max} = 0.0486 \times 10^{-10} + 0.10 \times 10^{-10}$$

$$= 0.148\,A^\circ$$

(iii) K.E of recoiled $e^\ominus = E_1 - E_2$

$$= \frac{hc}{\lambda} - \frac{hc}{\lambda'} = hc\left(\frac{\lambda'-\lambda}{\lambda\lambda'}\right)$$

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$$= 6.63\times10^{-34}\times3\times10^{8}\left[\frac{0.107\times10^{-10}-0.10\times10^{-10}}{0.10\times10^{-10}\times0.107\times10^{-10}}\right]$$

$$= 6.63\times10^{-34}\times3\times10^{8}\left[\frac{0.107-0.10}{0.10\times0.107\times10^{-10}}\right]$$

$$= 19.89\times10^{-26}\left[\frac{0.007}{0.0107}\times10^{+10}\right]$$

$$= \frac{19.89\times0.007}{0.0107}\times10^{-16}$$

$$= 6.54\times10^{-15}\ J.$$

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* K.E of recoil electron in Compton effect :-

The K.E of recoil electron is always less than 1 which shows that some photon always scattered

K.E = Energy of Incident photon - Energy of Scattered photon

$= E_1 - E_2$

$$K.E = \frac{hc}{\lambda} - \frac{hc}{\lambda'}$$

$\because \lambda' - \lambda = \frac{h}{m_0 c}(1 - \cos\theta)$

$$K.E = \frac{hc}{\lambda\lambda'}(\lambda' - \lambda)$$

$$K.E = \frac{hc}{\lambda\lambda'}\left[\frac{h}{m_0 c}(1 - \cos\theta)\right]$$

$$= \frac{hc}{\lambda\lambda'}\left[\frac{h}{m_0 c} \times 2\sin^2\theta/2\right]$$

$$= \frac{2h^2}{\lambda\lambda'}\sin^2\theta/2$$

$$K.E = \frac{2h^2 \sin^2\theta/2}{\lambda\left(\lambda + \frac{2h}{m_0 c}\sin^2\theta/2\right)}$$

$$K.E = \frac{hc}{\lambda^2}\frac{\left[2h/m_0 c\lambda \times \sin^2\theta/2\right]}{\left[1 + \frac{2h}{m_0 c\lambda}\sin^2\theta/2\right]}$$

for maximum K.E = $\theta = 180°$

$\sin\theta/2 = 1$

let $\frac{h}{m_0 c\lambda} = \alpha$

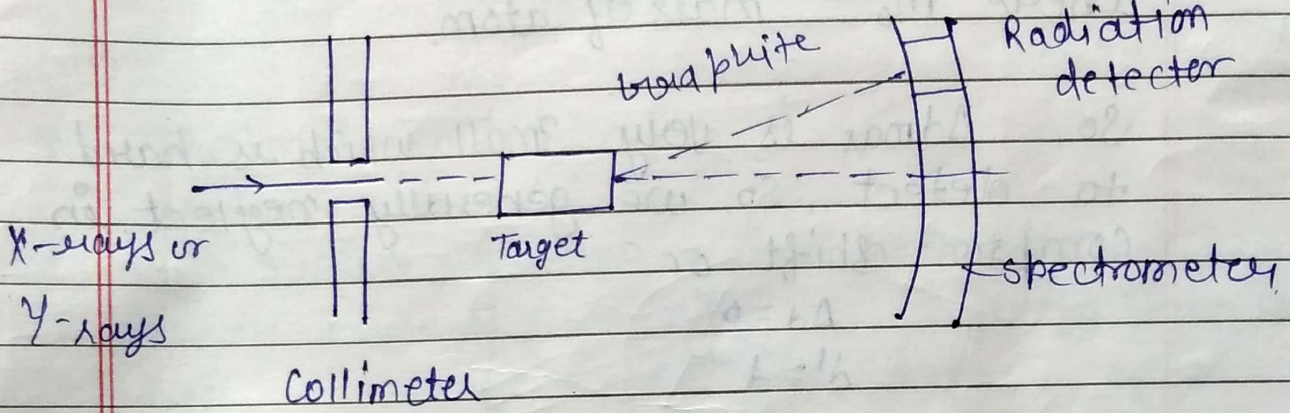
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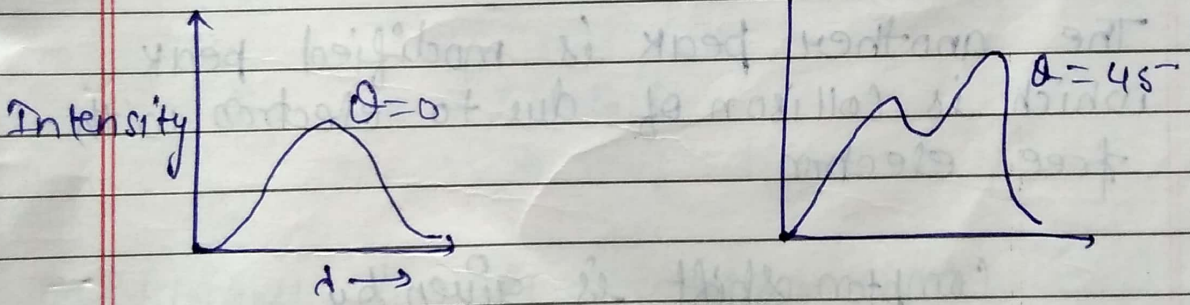
$$K.E = \frac{hc}{\lambda}\left[\frac{2\alpha}{1+2\alpha}\right]$$

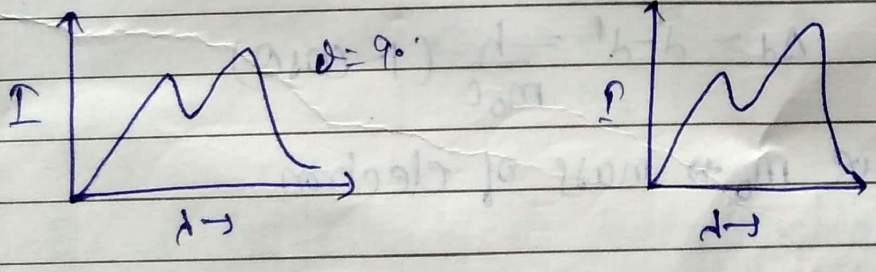
$\therefore KE < I$

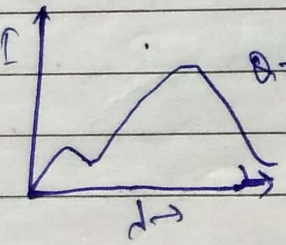
* Experimental verification of compton effect.

Presence of unmodified radiation with modified radiation in compton effect.









I) In Compton radiation in polar diagram we get three peak in which one is unmodified peak which is due to collision of photon with bound electron

For unmodified peak

$$\Delta\lambda = \lambda' - \lambda = \frac{h}{m_0 c}[1 - \cos\theta]$$

where m_0 – mass of atom.

So, $\Delta\lambda_{max}$ is very small which is hard to detect, so, we generally neglect in compton shift or

$$\Delta\lambda = 0$$
$$\lambda' = \lambda$$

II) The another peak is modified peak which is collison of due to electron with free electron.

Compton shift is given by

$$\Delta\lambda = \lambda' - \lambda = \frac{h}{m_0 c}(1 - \cos\theta)$$

where m_0 → mass of electron

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and its maximum value is $\Delta\lambda_{max}$ which is detectable and cannot be neglect.

$$\Delta\lambda_{max} = 0.0486\ \text{Å}$$

Compton shift is not visible in visable light

$$= \frac{0.0486}{4.86 \times 10^{3}} = 0.0069$$

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* Thermal Radiation:

Netwton's Law of cooling:

It is aplicable when there is small temp. diff. b/w obj. & surroundings.

$E = \sigma T^4$ — Perfectly black body

$E = \sigma e T^4$ → normal object

$$E = \sigma e [T - T_0]$$

$T - T_0 \Rightarrow$ Temp. difference

* Kirchoffs law of thermal radiations:

$$\boxed{E_\lambda = \frac{e_\lambda}{a_\lambda}}$$

$E_\lambda \Rightarrow$ Emissivity of Perfectly black body.

$e_\lambda \Rightarrow$ Emissivity of normal body

$a_\lambda \Rightarrow$ absorptivity " " "

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→ The ratio of Emissive Power to absorptive Power of any Body at a particular temp and for a given wavelength of light is equal to the emissive Power of Perfectly black body.

As we know that

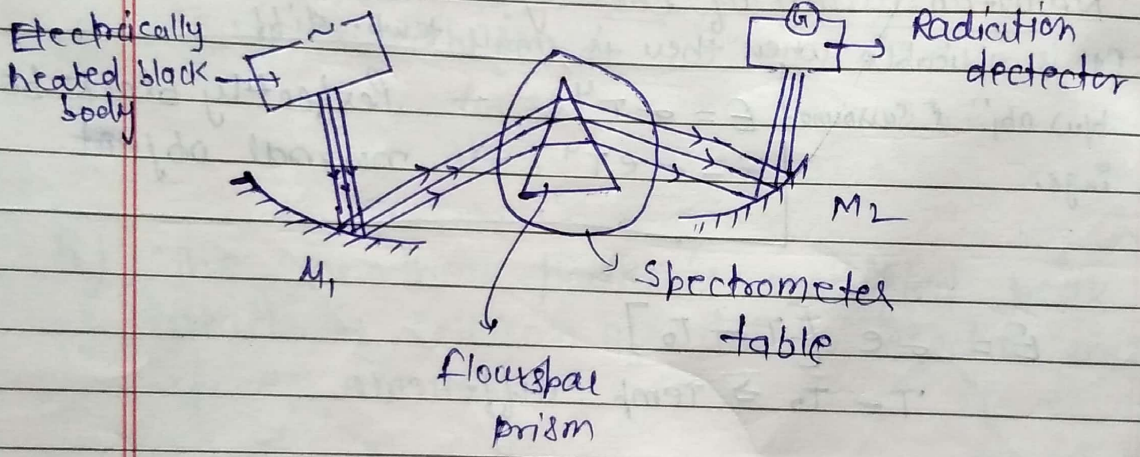
$$E_\lambda = 1$$

$$\boxed{e_\lambda = a_\lambda}$$

(1)

Imp.

* Black Body Radiation spectrum:

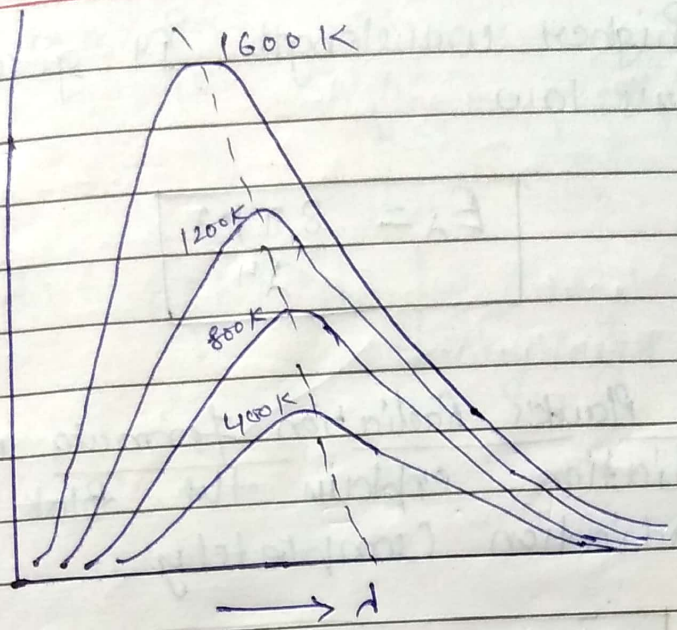


M_1 & M_2 → convex mirror

Experimental set up.

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Result:



(i) From the graph it is clear that Energy is not uniformly distributed at a Particular temp.

(ii) At a Particular temp. the area under the curve gives the total energy radiated per second at that Particular wavelength and it is given by Stephens Law

$$E \propto T^4 \Rightarrow \boxed{E = \sigma T^4}$$

(iii) At a particular temp. the maximum Energy As we change the temp. the maximum Energy Shifts towards the Lower wavelength. which is given by

$$\boxed{\lambda_m \cdot T = \text{Constant}}$$ → Wein's Law

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(iv) For higher wavelength. It gives the Rayleigh Jeau's law

$$E_\lambda = \frac{8\pi kT}{\lambda^4}$$

$E_\lambda = U_\lambda$

→ The Plank's Radiation formula of thermal radiation explain the ~~Blak~~ Black body radiation completely.

$$U_\lambda d\lambda = \frac{8\pi hc}{\lambda^5} \frac{d\lambda}{e^{hc/\lambda kT} - 1}$$

U_λ — energy density

For Lower wavelength or shorter wavelength

$\lambda << 1$ $\quad e^{hc/\lambda kT} >> 1$

$$U_\lambda d\lambda = \frac{8\pi hc}{\lambda^5} \times e^{-hc/\lambda kT} d\lambda$$

by calculating the integral of last eq^n it gives the Weiu's law of thermal radiation

For higher wavelength :

$$e^{hc/\lambda kT} = 1 + \frac{hc}{\lambda kT} + \cdots$$

1 - mark
5 - ① Fig. X,

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$$U_\lambda d\lambda = \frac{8\pi hc}{\lambda^5} \frac{d\lambda}{\left[1 + \frac{hc}{\lambda KT} + \cdots - X\right]}$$

$$\boxed{U_\lambda d\lambda = \frac{8\pi KT}{\lambda^4} d\lambda}$$ → Rayleigh Jeans law.

To mark

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Wave Mechanics

(*) **Duality principle :**

Light
EM radiation
- Photo electric effect, Compton effect → Particle
- Interference, diffraction, Polarization → wave

→ Light sometime behave as a particle and some time as a wave which shown the dual nature of light and it is also known as Duality principle.

- **de Broglie wave / Matter wave (or) de Broglie wavelength :**

de Broglie extending duality principle for ~~show~~ all macroscopic as well as microscopic particle.

- Acc. to de Broglie a material particle in motion has a wave associated with it and the wavelength of this wave is given by

$$\lambda = \frac{h}{P} = \frac{h}{mv}$$

$\lambda \rightarrow$ de Broglie wavelength
$P \rightarrow$ momentum of particle
$m \rightarrow$ mass of particle

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$v \Rightarrow$ velocity of Particle.

- Different forms of de Broglie wavelength

(I) If K.E of a free particle is given.

$$E = E_K$$

$$= \frac{1}{2} m v^2 \cdot \frac{m}{m}$$

$$= \frac{1}{2} \frac{(mv)^2}{m}$$

$$= \frac{1}{2} \frac{p^2}{m} = \frac{p^2}{2m} = E$$

$$p = \sqrt{2mE}$$

$$\boxed{\lambda = \frac{h}{p} = \frac{h}{\sqrt{2mE}}}$$

(II) if a particle is accelerated with Potential difference of V volt.

$$E_K = qV$$

$q \rightarrow$ charge of particle

$$\frac{p^2}{2m} = qV$$

$$p = \sqrt{2mqV}$$

$$\boxed{\lambda = \frac{h}{\sqrt{2mqV}}}$$

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(iii) If Particle in thermal equilibrium:

$$E_K = \frac{3}{2} K_B T$$

$K_B \rightarrow$ Boltzmann Constant
$T \rightarrow$ absolute temp. (K)

$$\frac{p^2}{2m} = \frac{3}{2} K_B T$$

$$p = \sqrt{3m K_B T}$$

$$\boxed{\lambda = \frac{h}{\sqrt{3m K_B T}}}$$

(iv) Relativistic form of de-Broglie wavelength

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

if Particle is moving near about velocity of light

$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}}$$

$$\lambda = \frac{h\sqrt{1 - v^2/c^2}}{m_0 v}$$

* Detection of matter waves:

(1) For macroscopic Particle / bodies:

Let us consider a ball of mass 10gm is moving with velocity 10m/s the

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de Broglie wavelength associated with ball

$$\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{6.63 \times 10^{-34}}{10 \times 10^{-3} \times 10} = 6.63 \times 10^{-33} \text{ m}$$

It is a very small value it can which can not be measurable

(ii) for microscopic particle:

Let an $e^{\ominus}$ is moving with velocity 10^5 m/s the de Broglie wavelength associated with $e^{\ominus}$

$$\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{6.63 \times 10^{-34}}{9.1 \times 10^{-31} \times 10^5}$$

$$\lambda \approx 6.6 \times 10^{-9} \text{ m}$$

It is measurable

From above two cases it is clear that in case of macroscopic particle de Broglie wavelength has very small value which can be neglect.

* Properties of matter waves:

(1) $\lambda = \frac{h}{p} = \frac{h}{mv}$ if $v = 0$

$\lambda \to \infty$

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It shows that matter waves always associated with moving particles

(ii) matter waves can be generate by charge or uncharge particle.

(iii) It is neutral in nature.

(iii) Velocity of matter waves depends on the velocity of matter particles

(iv) matter waves are not Electromagnetic waves

a) matter waves are neutral in nature where as E·M waves generate from the charge particle

b) Velocity of matter waves depends on the velocity of particle where as E·M waves have diff. velocity in diff. medium.

c) Velocity of E·M waves is equal to c where as the velocity of matter waves is always grater then c.

(v) Velocity of matter waves is grater then the velocity of light.

$$\lambda = \frac{h}{p} = \frac{h}{mv} \quad - (i)$$

$$v_p = v \cdot h \quad - (A)$$

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$E = h\nu$

$E = mc^2$ $\quad mc^2 = h\nu$

$\nu = \frac{mc^2}{h}$ ---(ii)

λ & ν → (i) & (ii) → A

$v_p = \frac{mc^2}{h} \cdot \frac{h}{m\nu}$

$v_p = \frac{c^2}{v}$ $\quad v < < c$

matter waves

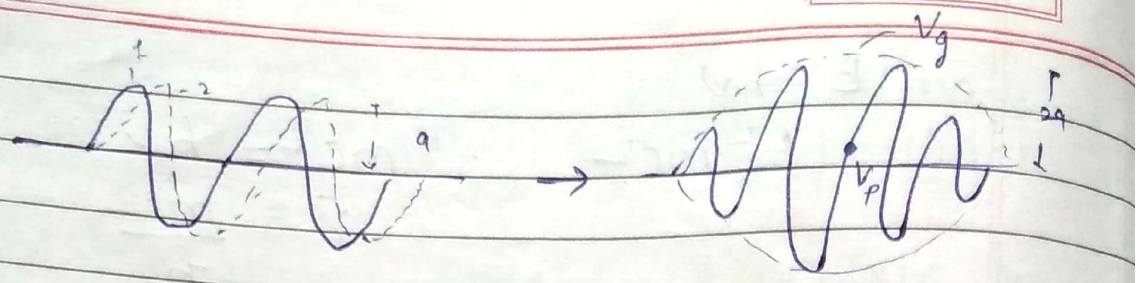
$v_p > c$

To solve this contradiction Shodinger gives the concept of wave packet. Acc. to which A moving particle is always associated with a group of wave whose velocity is known as velocity of group wave.

* Wave packets :

wave packet is a group of wave having slightly diff. frequencies and wave length but their phase and Amplitude are such that they interfair constractively over a small region of space where the particle can be located. Outside of the region they interfair distractively and Amplitude reduce to zero

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* Expression of group velocity and phase velocity.

Let us consider a wave packet is consist of two waves of having same ~~amplitude~~ amplitude but slightly diff. angular velocity ω_1 and ω_2 and wave vector K_1 and K_2

$$K_1 = \frac{2\pi}{\lambda}$$

The displacement of each wave is given by

$$y_1 = a \sin(\omega_1 t - K_1 x)$$
$$y_2 = a \sin(\omega_2 t - K_2 x)$$

The resultant displacement

$$Y = y_1 + y_2$$

$$= a\left[\sin(\omega_1 t - K_1 x) + \sin(\omega_2 t - K_2 x)\right]$$

$$= 2a\left[\sin\left[\left(\frac{\omega_1+\omega_2}{2}\right)t - \left(\frac{K_1+K_2}{2}\right)x\right]\cos\right.$$

$$\left.\times\left[\left(\frac{\omega_1-\omega_2}{2}\right)t - \left(\frac{K_1-K_2}{2}\right)x\right]\right.$$

$$y = \underbrace{2a\cos\left[\left(\frac{\omega_1-\omega_2}{2}\right)t - \left(\frac{K_1+K_2}{2}\right)x\right]}_{\text{modified amplitude}}\sin\left[\left(\frac{\omega_1+\omega_2}{2}\right)t - \left(\frac{K_1-K_2}{2}\right)x\right]$$

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Let us consider

$$\frac{\omega_1 - \omega_2}{2} = \Delta\omega \qquad \frac{K_1 - K_2}{2} = \Delta K$$

$$\frac{\omega_1 + \omega_2}{2} = \omega \qquad \frac{K_1 + K_2}{2} = K$$

$$y = 2a \cos[\Delta\omega t - \Delta K x) \sin(\omega t - Kx)$$

Now for group velocity $\Delta\omega t - \Delta K x = 0$

$$V_g \Rightarrow \frac{x}{t} = \frac{\Delta\omega}{\Delta K}$$

if wave packet is consist of more then 2 wave then

$$\Delta\omega = d\omega, \quad \Delta K = dk.$$

$$\boxed{V_g = \frac{d\omega}{dK}}$$ $V_g \rightarrow$ group velocity.

For phase velocity $\omega t - Kx = 0$

$$\frac{x}{t} = \frac{\omega}{K}$$ → average of all the angular velocity

↳ average of all the wave vector

$$\boxed{V_p = \frac{\omega}{K}}$$ Phase Velocity.

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* **Group Velocity :**

It is the velocity with which over all shapes of the wave amplitude known as modulation or at which the wave packet moves in the space

It is denoted by V_g.

$$V_g = \frac{d\omega}{dk} \quad \text{(1)}$$

* **Phase velocity :**

The average velocity of monochromatic individual wave in the medium with in the wave packet is known as phase velocity

It is denoted by V_p

$$V_p = \frac{\omega}{k}$$

* **Relation b/w group velocity and phase velocity**

As $V_g = \frac{d\omega}{dk}$ & $V_p = \frac{\omega}{k}$

$$V_g = \frac{d}{d\omega}[V_p \cdot k]$$

$$V_g = V_p + k\frac{d}{dk}V_p \quad \text{— (A)}$$

$\frac{1}{\lambda} \quad -\frac{1}{\lambda^2} 2\pi d\lambda$

$$V_g = V_p - \frac{d d V_p}{d\lambda}$$

(i) if velocity of wave depend on the wavelength then

$$V_g < V_p$$

(ii) if velocity does not depends on λ then

$$V_g = V_p$$

Hypothetical case

* Relation b/w group velocity and particle velocity:

$$V_g = \frac{d\omega}{dK}$$

$$= \frac{d(E/\hbar)}{d(P/\hbar)}$$

$$V_g = \frac{dE}{dP} \quad \text{— (A)}$$

$E = h\nu$

$= \frac{h \cdot \omega}{2\pi}$

$E = \hbar\omega$

$K = \frac{2\pi}{\lambda} = \frac{2\pi P}{h}$

$P = \frac{h}{2\pi} \cdot K$

$P = \hbar K$

(i) For non-relativistic Particle :

$$E = \frac{1}{2} m v^2$$

$$E = \frac{p^2}{2m}$$

$$dE = \frac{2p\,dp}{2m}$$

$$\frac{dE}{dp} = \frac{p}{m} = \frac{mv}{m} \quad \text{---(1)}$$

$$\frac{dE}{dp} = v$$

$$\boxed{v_g = v}$$

(ii) Relativistic Case :

$$E^2 = p^2c^2 + m_0^2c^4$$

$$2E\,dE = 2pc^2\,dp + 0$$

$$\frac{dE}{dp} = \frac{pc^2}{E}$$

$$p = mv = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} v$$

$$\frac{dE}{dp} = \frac{pc^2}{E} = \frac{mvc^2}{mc^2}$$

$$\frac{dE}{dp} = v \qquad \boxed{v_g = v}$$

$E^2 = p^2c^2 + m_0^2c^4$

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→ what is the Phase velocity of a non relativistic free particle.

$v_g = v$

$v_p - \frac{d}{d\lambda} v_p = v$

$v_p = v + \lambda \frac{d v_p}{d\lambda}$

$v_p = v \cdot \lambda$

$= \frac{E}{\lambda} \lambda$

$= \frac{1}{2} m v^2 \times \frac{h}{\lambda}$

$= \frac{\omega}{2\pi} \cdot \lambda = \frac{\omega}{2\lambda} = \frac{\omega v}{2c}$

$v_p = v \cdot \lambda$

$v_p = \frac{1}{2} \frac{m v^2}{h} \cdot \lambda$

$v_g = v$

$E = h\upsilon \quad : \quad \upsilon = \frac{E}{h}$

$v_p = \frac{E}{h} \cdot \frac{h}{p} = \frac{E}{p} = \frac{\frac{1}{2} m v^2}{p}$

$\frac{E}{p} = \frac{p^2/2m}{p} = \frac{p}{2m} = \frac{mv}{2m} = \frac{v}{2}$

$v_p = \frac{v}{2} = \frac{v_g}{2}$

$v_p = \frac{c^2}{v}$

$v_p = \frac{v}{2}$ or $\frac{v_g}{2}$

$\frac{c}{\lambda} = \frac{hc}{\lambda} = c = v$

$\frac{1}{2} m v^2 = h\upsilon$

$\upsilon = \frac{\frac{1}{2} m v^2}{h}$

$p = \frac{h}{\lambda} \quad \upsilon = \frac{c}{\lambda}$

$\frac{c}{\lambda} = v$

$\frac{1}{2} m v^2 = \frac{hc}{\lambda}$

$\frac{\frac{1}{2} m v^2}{h} = \frac{c}{\lambda}$

$\frac{m v^2}{h} \cdot \lambda = v$

$E = mc^2$

SK-Gupt.

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Que:- The Photo electric threshold wavelength of λ is 5000 A°. Find
(i) the value of work function in eV
(ii) K.E of the Photo electrons in eV is acted by wavelength 4000 A°.

Sol:- $\lambda_0 = 5000\ A^\circ$

$E = h\nu_0 + K.E$

$= h\nu - h\nu_0 = K.E$

$= h\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right) = K.E$

$\omega = \frac{hc}{\lambda_0}$

$= \frac{6.62 \times 10^{-34} \times 3 \times 10^{8}}{5000 \times 10^{-10}}$

$= \frac{6.62 \times 3 \times 10^{-16}}{5000}$

$= \frac{19.86 \times 10^{-19}}{5}$

$= 3.97 \times 10^{-19}$

in e^Θ volt $= \frac{3.97 \times 10^{-19}}{1.6 \times 10^{-19}} = \frac{3979}{1600} = \frac{397}{160}$

$= 2.4$

$E = \omega + K.E$

$\frac{hc}{\lambda} - \omega = K.E$

$\frac{19.86 \times 10^{-16}}{5000 \times 10^{-10}} - 2.4 = K.E.$

$\frac{19.86}{5} \times 10^{-9} = 3.$

$KE = h\nu - h\nu_0$

$K.E = 0.27$

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$$\frac{19.86 \times 10^{-26}}{4000 \times 10^{-26}} = 2.4 \approx K.E$$

$$\frac{19.86}{4} \times 10^{-9} - 2.4 = K.E$$

$$\frac{4.96 \times 10^{-9}}{1.6 \times 10^{-19}}$$

$$\frac{4.96 \times 10^{-9}}{1.6 \times 10^{-19}} = 3.1 - 2.4$$

$$= 0.$$

(2) In a photo electric emission from a given target the velocity of emitted electrons is 1×10^6 m/s then light of wave length 2.5×10^{-7} m is used Calculate

(i) velocity of emitted electrons with light of wavelength 5×10^{-7}

(ii) work function of Photo cathode in ev.

$v_e = 1 \times 10^6$, $\lambda_1 = 2.5 \times 10^{-7}$

$v = 8.6 \times 10^5$ m/s

$$\frac{1}{2} m v_1^2 = h\nu_1 - h\nu_0$$

$$\frac{1}{2} m v_2^2 = h\nu_2 - h\nu_0$$

$$\frac{1}{2} m (v_1^2 - v_2^2) = h(\nu_1 - \nu_2)$$

$h\nu_1 = h\nu_0 - KE$

$h\nu_2 = h\nu_0 - KE$

$E_1 = \frac{hc}{\lambda_1}$

$E_2 = \frac{hc}{\lambda_2}$

$\frac{1}{2} m v^2 = e v_0$

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$$\frac{1}{2} \times 9.1 \times 10^{-31} \left(10^6 - v_2^2 \right) = 6.63 \times 10^{-34} \left(0.6 \times 10^{15} \right)$$

$$v_2^2 = 10^6 - 8.19 \times 10^{13}$$

$$v_2 =$$

In Rough N.B

1.57

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Q. the work function of K is 2ev then when U.V light of $\lambda = 3500\ A^0$ falls on K Surface Calculate the maximum K.E of emitted ~~Pt~~ in ev

$$\omega = 2ev.$$
$$\lambda = 3500 A^0$$

$$\frac{hc}{\lambda} - \omega = KE.$$

Conv. in ev. $\quad \frac{19.86}{3500 \times 10^{-10}} - 2ev = KE$

Q. Calculate the de Broglie wavelength associated with an e of K.E 4.55 ev

$$\lambda = \frac{h}{p}$$

$$\lambda = 6.6$$

$$\frac{p^2}{2m} = 4.55$$

$$p^2 = 2 \times 4.55 \times m$$
$$p^2 = 9.00 \times m$$
$$p^2 = 9 \times 9.1 \times 10^{-31}$$
$$= 81.9 \times 10^{-31}$$
$$= \frac{81.9 \times 10^{-31}}{1.6 \times 10^{-19}}$$
$$= \frac{819}{16} \times 10^{-12}$$
$$= 51.1 \times 10^{-12} eV.$$

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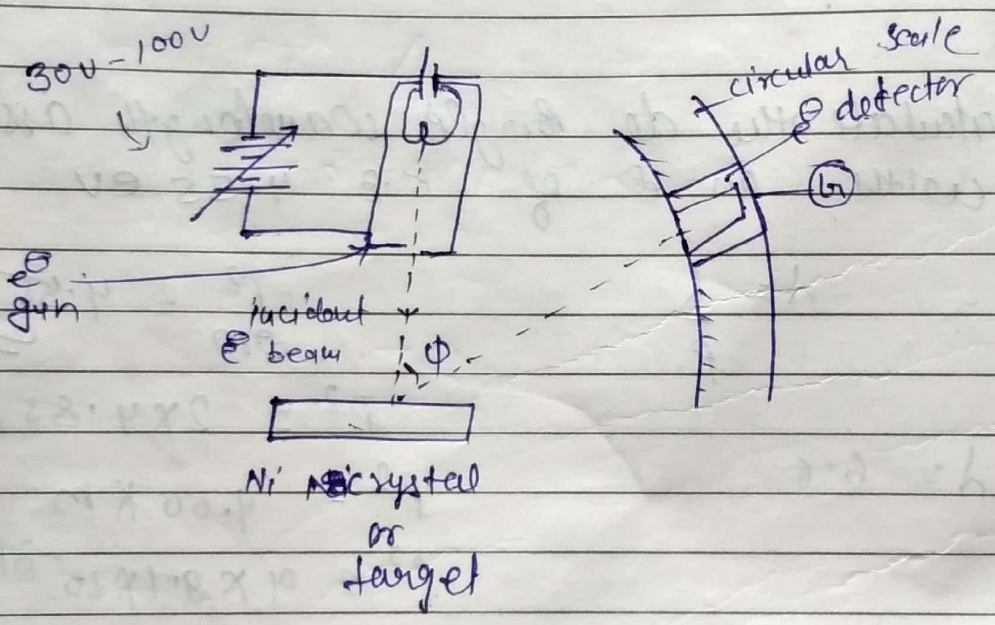
Q. A Proton and an e^- are during the same K.E then do their de-Broglie wave length.

$$\lambda = \frac{h}{p} \Rightarrow \lambda = \frac{h}{mv}$$

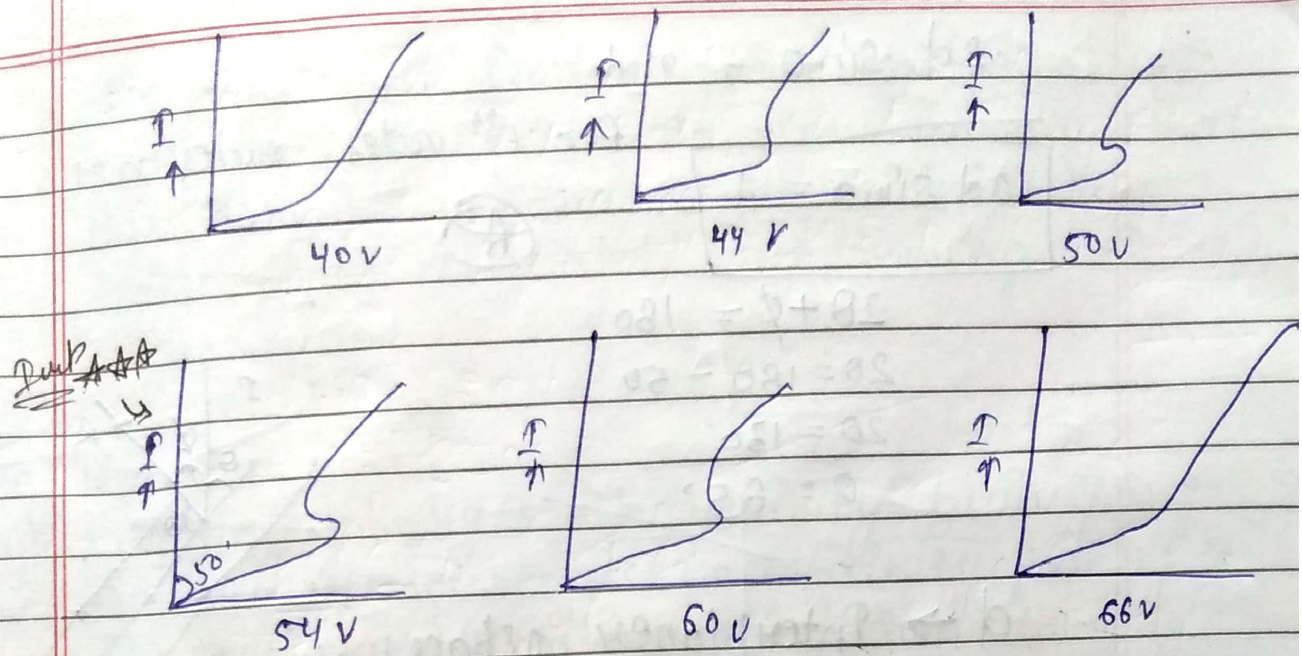
$$\lambda = \frac{h}{\sqrt{2mKE}}$$

* Experimental Verification of matter waves:
or
Davisson Germer Experiment

Imp.



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Polar diagram

→ the Polar curves only explain if we assume that their is always wave associated with the electron.

→ At low voltage (40 V) their is a smooth curve b/w current and angle of scattering of electron.

→ By increasing the voltage there is deflection in smoothness of curve which is due to association of matter waves with $e^{\ominus}$.

→ this deviation or deflection is most for at 54 volt and scattering angle of 50°

→ By using the Bragg's equation of x-ray diffraction

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$2d \sin\theta = n\lambda$

for 1st order $n = 1$

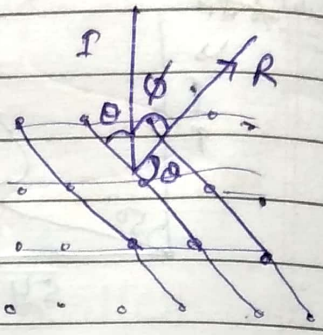
$$\boxed{2d \sin\theta = \lambda} \quad \text{(A)}$$

$2\theta + \phi = 180$

$2\theta = 180 - 50$

$2\theta = 130$

$\theta = 65°$



$d \rightarrow$ Interplaner spaces.

For Ni crystal $d = 0.91\ A°$

From eqn (A)

$$2d \sin\theta = \lambda$$

$$2 \times 0.91 \times 10^{-10} \times \sin 65° = \lambda$$

$$\lambda \simeq 1.65\ A°$$

Why de-Broglie wavelength of matter waves

$$\lambda = \frac{h}{p}$$

$$\lambda = \frac{h}{\sqrt{2mqV}} \quad \text{(3)}$$

$V = 54$ Volt

$$\lambda = \frac{6.63 \times 10^{-34}}{\sqrt{2 \times 9.1 \times 10^{-31} \times 1.6 \times 10^{-19} \times 54}}$$

$$\lambda \simeq 1.67\ A°$$

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the wavelength coming from eqn (A) and (B) are nearly equal So, we can say that our assumption that there is always ~~base~~ wave associated with moving e⊖ are correct

Statement Uncertainty

Prob ~~Hin~~ Heisenberg's Uncertainity principle :-
Acc. to Heisenberg's uncertainity principle it is impossible to determine simultaneously the exact position and momentum of a particle. there is always some uncertainity either in the value of momentum or position.

→ If Δp → uncertainity in momentum
Δx → " " position
then

$$\Delta p \cdot \Delta x = \hbar \text{ or } > \frac{\hbar}{2}$$ J-Sec

$$\Delta p_x \cdot \Delta x = \hbar$$
$$\Delta p_y \cdot \Delta x = 0$$ (R)

$$\hbar = \frac{h}{2\pi} = 1.05 \times 10^{-34} \text{ J Sec}$$

use for Num. →
$$\Delta E \cdot \Delta t = \hbar$$
$$\Delta J \cdot \Delta \theta = \hbar$$

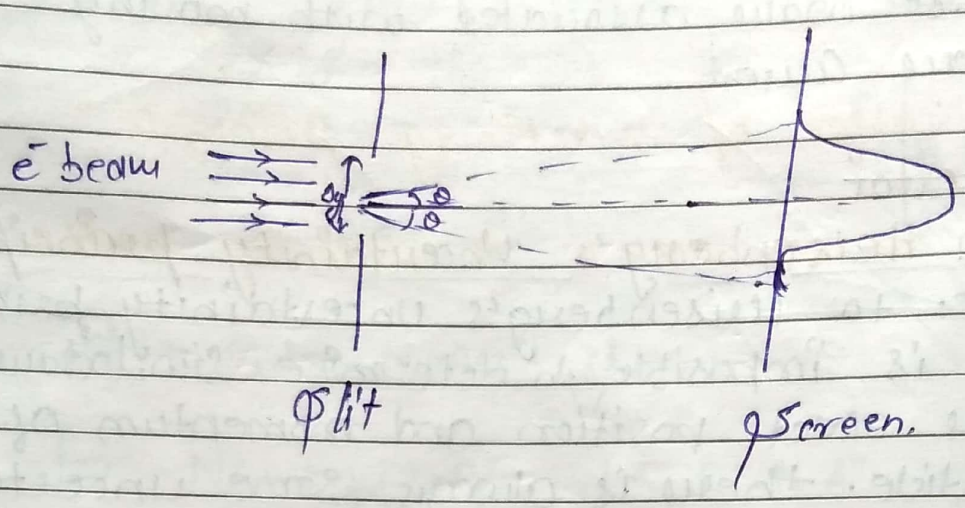
ΔE → uncertainity in Energy
Δt → uncer. " " time
ΔJ → " " Angular momentum
$\Delta \theta$ → " " Angle

J.S is chemicaly conjugate.

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* Experimental illustration of uncertinity principle :

by e^- diffraction :



⇒ the maximum uncertinity the position of e^- at the slit = Δy (width of slit)

$$e \sin\theta = \lambda$$

By first order differenciation

$$\Delta y \sin\theta = \lambda$$

$$\Delta y = \frac{\lambda}{\sin\theta} \quad - (1)$$

⇒ Uncertinity in momentum :

$$\Delta P_y = 2P \sin\theta$$

$$\Delta P_y = \frac{2h}{\lambda} \sin\theta \quad - (2)$$

$$\Delta y \cdot \Delta P_y = \frac{\lambda}{\sin\theta} \cdot \frac{2h}{\lambda} \sin\theta = 2h$$

Radius = 1Fm $\approx 1 \times 10^{-15}$ m

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$$\Delta y \cdot \Delta P_y = \frac{h}{2}$$

$$\boxed{\Delta y \cdot \Delta P_y > \hbar \text{ or } \geq \frac{\hbar}{2}}$$

* Application of Uncertinity principle :

4. Imp ☆ 1. e^- can not reside in side the nucleus. Imp.
2. Energy of e^- in a potential Box.
3. Finite width of spectral lines.
4. Binding energy of H atom
5. " " " atom.
6. " " " Harmonic Oscillation (1, 4, 3)

M. Imp 1. e^- can not reside inside the nucleus :

Let us assume that e^- reside inside the nucleus

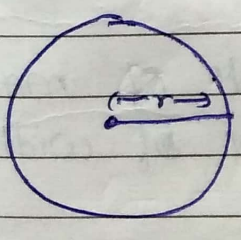
radius of any nucleus of an atom $\approx 10^{-14}$ m.

the maximum uncertinity in position of e^- inside the nucleus $= \Delta x_{max} = 2 \times 10^{-14}$ m ——— (1)

from uncertinity principle

$$\Delta P_{min} \cdot \Delta x_{max} = \hbar$$

$$\Delta P_{min} = \frac{\hbar}{\Delta x_{max}}$$



3-4 MeV

$E_0 = m_0c^2$
$= 0.51$ MeV

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$$\Delta P = \frac{\hbar}{2\times10^{-14}} = \frac{1.05\times10^{-34}}{2\times10^{-14}}$$

$\Delta P_{min} = 5.275\times10^{-21}$ Kgm/sec $-(ii)$

From Relativistic total energy of $e^{\ominus}$ in terms of momentum

$$E^2 = p^2c^2 + m_0^2c^4$$

$$= (5.275\times10^{-21})^2\times(3\times10^8)^2 + (0.51)^2 \quad (9.1\times10^{-31})^2\times(3\times10^8)^4$$

2nd term have very small value
So, Neglect

$$E_{min}^2 = p^2c^2$$
$$E_{min} = PC = 5.275\times10^{-21}\times3\times10^8 = 9.8\text{ MeV}$$

From experiment the maximum energy of an electron is 3-4 MeV. And according to our assumption minimum energy required to reside inside the nucleus should be 9.8 MeV, so our assumption is wrong.

Energy of an e⁻ in a 1D Potential box:

Let us Consider a particle of mass m exist in a potential box of width L

width of box = L
mass of Particle = m

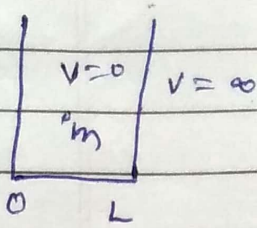
10^{-8} sec — max.

Bohr radius = 0.53 Å

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E
2

According to uncertinity principle



$$\Delta p_{min} \Delta x_{max} = \hbar \quad -(1)$$

$$\Delta x_{max} = L$$

$$\Delta p_{min} = \frac{\hbar}{L}$$

then total Energy of particle $E_{min} = \frac{p^2}{2m}$

$$\boxed{E_{min} = \frac{\hbar^2}{2mL^2}}$$

3. Finite width of Spectral Line:

Acc. to uncertinity principle

$$\Delta E_{min} \cdot \Delta t_{max} = \hbar$$

$$\Delta t_{max} = 10^{-8} \text{ sec.}$$

$$\Delta E_{min} = \frac{\hbar}{10^{-8}} = 1.05 \times 10^{-26} \text{ Joule}$$

As energy has a finite value, it shows that energy spectrum as finite width of each spectrum line.

0.53 Å

4. Bohr's radius Or binding energy of H atom:

Let us Consider Δp and Δx_{max} are the uncertinity in momentum and position of e^- in 1st orbit.

acc. to uncertinity principle

$$\Delta p_{min} \cdot \Delta x_{max} = \hbar$$

$$\Delta p_{min} = \frac{\hbar}{\Delta x_{max}}$$

then the minimum total energy of $e^{\ominus}$ in 1st orbit

$$E = K.E + P.E$$

$$= \frac{p^2}{2m} - \frac{Ze^2}{\Delta x}$$

$$E = \frac{\hbar^2}{2m\Delta x_{max}^2} - \frac{Ze^2}{\Delta x} \quad \text{--- (2)}$$

For minimum or maximum value of E

$$\frac{dE}{d\Delta x} = 0, \qquad \frac{d^2E}{d\Delta x^2} = +ve$$

differentiate 2nd eq (2) with respect to Δx from eq (2)

$$\frac{dE}{d\Delta x} = \frac{-2\hbar^2}{2m\Delta x^3} - \frac{Ze^2}{\Delta x^2} = 0$$

$$\frac{\hbar^2}{m\Delta x^3} = \frac{Ze^2}{\Delta x^2} \Rightarrow$$

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$$\Delta x = \frac{\hbar^2}{mze^2}$$

$\Delta x = 0.53\ A^\circ$

it is Bohrs radius which is the radius of 1st orbit for hydrogen atom and its value is $0.53\ A^\circ$

$$\frac{d^2E}{d\Delta x^2} = +ve$$

for

Binding Energy.

$$\frac{d^2E}{d\Delta x^2} = \frac{3\hbar^2}{m\Delta x^4} - \frac{2ze^2}{\Delta x^3}$$

Subst. the value of ΔX

$$\frac{d^2E}{d\Delta x^2} = \frac{3\hbar^2}{m \times (0.53A^\circ)^4} - \frac{2ze^2}{\Delta x^3}$$

$$= \frac{3 \times 1.05 \times 10^{-34}}{9.1 \times 10^{-31} (0.53A^\circ)^4} - \frac{2 \times 1 \times (1.6 \times 10^{-19})^2}{1}$$

$= +ve$

It show that it is the minimum energy required for an e^- to bind with the nucleus of Hydrogen atom

$-\Delta E_{min} = (1 - 15z)\ eV.$

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for $n = 1$

$E_{min} = (1-15)\ eV$

$= 14\ eV.$

* Binding Energy of an atom:

$$\frac{d^2E}{d\Delta x^2} = +ve$$

$$\frac{d^2E}{d\Delta x^2} = \frac{3\hbar^2}{m\Delta x^4} - \frac{2e^2}{\Delta x^3}$$

Substitute $\Delta x = \frac{\hbar^2}{m^2e^2}$

$= +ve$

$E_{min} = (1-15Z)\ eV.$

* Binding Energy of Harmonic Oscillation:

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* Wave function (or) Born's Explanation of wave function : $\Psi(r,t)$:

(a)

(1) Wave function is representing by $\Psi(r,t)$

(2) It represent the state of particle at a particular time in a wave packet.

(3) $\Psi(r,t)$ is a complex Quantity, which has no physical significance

(4) $\Psi(r,t) \times \Psi^*(r,t)$ = Probability → (Born's expl.)

$\Psi^*(r,t)$ = Complex Conjugate of Ψ.

(5) $$\int_{-\infty}^{\infty} \psi^* \psi \, d\tau = 1 \qquad \text{—— (1)}$$

when we calculate the Probability of in Complete Space then it is equal to 1 and it is given by eq^n (1)

$d\tau = dx\,dy\,dz.$

this eq^n is also known as normalized condition of wave fn

Imp (b) Necessary Conditions of wave fn :

(1) wave fn should be Normalised.

Satisfy $$\int_{-\infty}^{\infty} \psi^* \psi \, d\tau = 1$$

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(ii) wave fn should be single valued

(iii) wave fn should be continious.

(iv) " " " " finite

$\psi = e^{-ix}$

* Schrodinger wave eq^n :

Ans

Time independent
(e moves in a particular orbit).

Time dependent

Ans * Time independent Schrodinger wave eq^n :

Schrodinger Time Ind. eq^n is the Partial diff of wave fn in terms of two variables.

- In time independent schro. wave eq^n Potential Energy is only the function of position.
- Let us consider A system of stationary wave associated with the Particle which is moving with velocity v.
- In general wave eq^n is given by

$$\frac{d^2y}{dx^2} = \frac{1}{v^2}\frac{d^2y}{dt^2}$$

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In terms of wave function (ψ)

$$\frac{d^2\psi}{dx^2} = \frac{1}{v^2}\frac{d^2\psi}{dt^2} \quad \text{— (A)}$$

[$v \rightarrow$ Particle velocity
$v = v_g$]

Let us assume that the sol^n of eq^n (A)

$$\psi(x,t) = \psi_0 e^{-i\omega t}$$

(f^n of x)

Now if this is the sol^n of eq^n (A) then it should satisfy the eq^n (A)

$$\frac{d\psi}{dx} = \frac{d\psi_0}{dx} e^{-i\omega t}$$

$$\frac{d^2\psi}{dx^2} = \frac{d^2\psi_0}{dx^2} e^{-i\omega t} \quad \text{— (1)}$$

$$\frac{d\psi}{dt} = -i\omega \psi_0(x) e^{-i\omega t} \qquad (i^2 = -1)$$

$$\frac{d^2\psi}{dt^2} = -\omega^2 \psi_0(x) e^{-i\omega t} \quad \text{— (2)}$$

Sub the eq^n (1) and (2) in eq^n (A)

$$\frac{d^2\psi_0}{dx^2} e^{-i\omega t} = \frac{1}{v^2}\left(-\omega^2 \psi_0(x) e^{-i\omega t}\right)$$

$$\left(\frac{d^2\psi_0(x)}{dx^2} + \frac{\omega^2}{v^2}\psi_0(x)\right) e^{-i\omega t} = 0$$

↑ moment shows $\neq 0$

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$$e^{-i\omega t} \neq 0$$

$$\frac{d^2\psi_0(x)}{dx^2} + \frac{\omega^2}{v^2}\psi = 0$$

$$\frac{d^2\psi}{dx^2} + \frac{\omega^2}{v^2}\psi = 0 \quad \text{— (B)}$$

~~$\omega = 2\pi\nu$~~ $\omega = 2\pi\nu$

$$\omega = 2\pi\frac{v}{\lambda}$$

$$\frac{\omega}{v} = \frac{2\pi}{\lambda} \qquad \lambda = \frac{h}{p}$$

$$\frac{\omega}{v} = \frac{2\pi}{h}\cdot p$$

$$\frac{\omega}{v} = \frac{p}{\hbar} \qquad \text{Sub in (B)}$$

$$\frac{d^2\psi}{dx^2} + \frac{p^2}{\hbar^2}\psi = 0$$

Now total energy of Particle.

$$E = \frac{p^2}{2m} + V \qquad V \rightarrow \text{Potential energy}$$

$$p^2 = 2m(E-V)$$

$$\boxed{\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2}(E-V)\psi = 0} \quad \text{(1D)}$$

If the Particle moving in 3D space

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$$\frac{d^2\psi}{dx^2} + \frac{d^2\psi}{dy^2} + \frac{d^2\psi}{dz^2} + \frac{2m}{\hbar}[E-V]\psi(x,y,z,t) = 0$$

If Particle is a free particle

$$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2}E\psi = 0 \qquad V=0$$

Q.1 Find the energy of a proton in electron volt which have de-Broglie wavelength 1.2 A°

$$\lambda = 1.2\,A^\circ = 1.2\times10^{-10}\,m \qquad \lambda = \frac{h}{\sqrt{2mE}}$$

$$E = \frac{p^2}{2m} \Rightarrow \qquad p = \frac{h}{\lambda}$$

$$= \frac{6.63\times10^{-34}}{1.2\times10^{-10}}$$

$$= \times10^{-24}$$

$$= 5.52\times10^{-24}$$

$$1.6\times10^{-27} = \frac{(5.52\times10^{-24})^2}{2\times(9.1\times10^{-31})}$$

$$= \frac{30.4\times10^{-48}}{18.2\times10^{-31}}$$

$$= 1.67\times10^{-17}$$

$$= \frac{30.4\times10^{-48}}{3.2\times10^{-27}} = \frac{9.5\times10^{-21}}{1.6\times10^{-19}}$$

$$= 5.9\times10^{-2}$$

$$= 0.059\ eV$$

$\hbar = 1.054$

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(4) An $e^{\ominus}$ have speed 500 m/s with an accuracy of 0.01 %. Calculate the certainty with which its Position can be located.

$$\Delta p_{max} \times \Delta x_{min} = \hbar$$

$$\Delta x_{min} = \frac{\hbar}{\Delta p_{max}}$$

$$\Delta x = \frac{1.054 \times 10^{-34}}{mv}$$

$$= \frac{1.054 \times 10^{-34}}{9.1 \times 10^{-31} \times 500 \text{ m/s}}$$

$$= \frac{1.05 \times 10^{-34}}{9.1 \times 10^{-31} \times 5}$$

$$= \frac{1.05}{45} \times 10^{-3}$$

$$\Delta x = \frac{0.02 \times 10^{-3} \times 1 \text{ m}}{}$$

$$= 0.02 \times 10^{-1}$$

0.1 cm $\quad 0.2 \text{ Å}$

$\Delta P =$

0.116

0.42×10

$2 \times 1.6 \times 10^{-27}$

Mass of Proton

1.67×10^{-27}

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Q. An e^- is confined of length 10^{-8} m Calculat the minimum uncertainity in its m/u velocity

$\Delta P = ?$

$m \times v \times \Delta x = 1.054 \times 10^{-34}$

$m \times v = \frac{1.054 \times 10^{-34}}{10^{-8}}$

$v = \frac{1.054 \times 10^{-34}}{10^{-8} \times 9.1 \times 10^{-31}}$

$v = \frac{1.054}{9.1} \times 10^{-34+31+8}$

$= 0.11 \times 10^{5}$ m/s

Q. A Nucleon is confined to a nucleus of $r = 5$ fm Calculate the minimum K.E of the Neulon.

52 KeV

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Q. An $e^{\ominus}$ and proton have the same velocity compare the wavelength and the face and group velocities of their de-Broglie wave.

$$\lambda = \frac{h}{\sqrt{2mKE}}$$

$$\lambda_1 = \frac{h}{m_1 v_1} \quad \text{--- } e^{\ominus}$$

$$\lambda_2 = \frac{h}{m_2 v} \quad \text{proton}$$

$$\frac{\lambda_1}{\lambda_2} = \frac{m_2}{m_1}$$

$$\frac{\lambda_1}{\lambda_2} = \frac{1.6 \times 10^{-27}}{9.1 \times 10^{-31}}$$

$$= \frac{1.6}{9.1} \times 10^{4}$$

$$\frac{\lambda_1}{\lambda_2} = 0.17 \times 10^{4}$$

$$V_p = \frac{\omega}{K} = \frac{2\pi\nu}{\frac{2\pi}{\lambda}} = \frac{v\lambda}{\lambda}$$

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Q. At what speed the de-Broglie wave associated with a particle is equal to twice the wavelength.

$$\lambda = 2 \times 0.0243 \times 10^{-10}$$

$$\lambda = 0.0486 \times 10^{-10}$$

$$\frac{h}{p} = \lambda$$

$$\frac{h}{mv} = 0.0486 \times 10^{-10}$$

$$v = \frac{h}{m} \times 0.0486 \times 10^{-10}$$

$$= \frac{6.63 \times 10^{-34}}{9.1 \times 10^{-31}} \times 0.0486 \times 10^{-10}$$

$$= 0.73 \times 10^{-3} \times 0.0486 \times 10^{-10}$$

$$= 0.035 \times 10^{-13}$$

$\frac{c}{\sqrt{5}}$

$\frac{2.3 \times 10^8}{\sqrt{5}} = 1341$

$$\lambda = 2\lambda_c$$

$$\frac{h}{mv} = \frac{2h}{m_0 c}$$

$$\frac{h}{\frac{m_0 v}{\sqrt{1-\frac{v^2}{c^2}}}} = \frac{2}{m_0 c} = \frac{2}{c}$$

$$\sqrt{1-\frac{v^2}{c^2}} = \frac{2v}{c}$$

$$1 - \frac{v^2}{c^2} = \frac{4v^2}{c^2}$$

$$\frac{4v^2}{c^2} + \frac{v^2}{c^2} = 1$$

$$\frac{5v^2}{c^2} = 1$$

$$v = \frac{c}{\sqrt{5}}$$

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Schrodinger time dependent eq^n:

(1) From Schrodinger time independent:

$$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2}[E-V]\psi = 0 \quad -(i)$$

From time independent eq^n eliminate total energy in terms of variation of time

Now

$$\psi = \psi_0 e^{i\omega t}$$

$$\frac{d\psi}{dt} = \psi_0 e^{-i\omega t}(-i\omega)$$

$$\frac{d\psi}{dt} = -i\omega\psi$$

We know that

$$E = \hbar\omega$$

$$\omega = \frac{E}{\hbar}$$

$$\frac{d\psi}{dt} = -\frac{iE}{\hbar}\psi$$

$$-\frac{\hbar}{i}\frac{d\psi}{dt} = E\psi$$

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multiply by (i)

$$\frac{-\hbar i}{i^2} \cdot \frac{d\psi}{dt} = E\psi \quad -(ii)$$

$$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2}[E - V)\psi = 0$$

$$\frac{-\hbar^2}{2m} \cdot \frac{d^2\psi}{dx^2} + V\psi = E\psi \quad -(iii)$$

Substitute $E\psi$ from (ii) to (iii)

$$\frac{-\hbar^2}{2m} \cdot \frac{d^2\psi}{dx^2} + V\psi = i\hbar \frac{d\psi}{dt}$$

$$\frac{-\hbar^2}{2m} \nabla^2\psi + V\psi = i\hbar \frac{d\psi}{dt}$$

where

∇^2 = Laplacian operater

$$\nabla^2 = \frac{d^2}{dx^2} + \frac{d^2}{dy^2} + \frac{d^2}{dy^2}$$

$$H\psi = E\psi$$

$\hat{H}$ → Hamiltonian operater

$$\hat{H} = \frac{-\hbar}{2m} + \nabla^2 + V$$

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(3) Schrodinger time dependent eq^n :-

Let us consider a particle is moving velocity v and there are wave associated with particles and wave eq^n of these wave are given by

$$\frac{d^2\psi}{dx^2} = \frac{1}{v^2}\frac{d^2\psi}{dt^2} \quad \text{— (1)}$$

Now let $\psi = e^{-i(\omega t - kx)}$

(i) is the solution of eq^n (1) then

$$\frac{d\psi}{dx} = ik\psi \qquad k = \frac{2\pi}{\lambda}$$

$$\frac{d^2\psi}{dx^2} = -\frac{p^2}{\hbar^2}\psi \qquad = \frac{2\pi}{h}\cdot p$$

$$k = \frac{p}{\hbar}$$

$$p^2 = \frac{-\hbar^2}{\psi}\frac{d^2\psi}{dx^2} \quad \text{— (2)}$$

$$\frac{d\psi}{dt} = -i\omega\psi$$

$$\frac{d\psi}{dt} = -\frac{iE}{\hbar}\psi$$

$$E = \frac{-i\hbar}{\psi}\frac{d\psi}{dt} \quad \text{— (3)}$$

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total Energy

$$E = K.E + P.E$$

$$E = \frac{p^2}{2m} + V \quad \text{---------- (A)}$$

Substituting value from (2) and (3) to (A)

$$\frac{i\hbar}{\psi}\frac{d\psi}{dt} = \frac{-\hbar^2}{2m\psi}\frac{d^2\psi}{dx^2} + V$$

$$\boxed{i\hbar\frac{d\psi}{dt} = \frac{-\hbar^2}{2m}\frac{d^2\psi}{dx^2} + V\psi}$$

for a free Particle

$$i\hbar\frac{d\psi}{dt} = \frac{-\hbar^2}{2m}\frac{d^2\psi}{dx^2}$$

* Application of Schrodinger eq^n:

(1) Particle in one dimension Potential box
(2) Particle in 3 D Potential box.

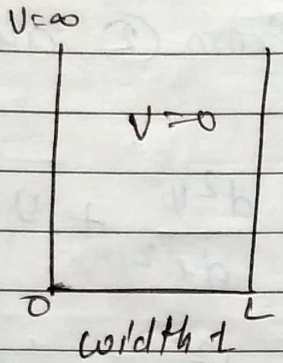
(1) Particle in one D Potential Box:
with help of schrodinger eq^n we can find the energy value and energy function of a partide

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Let us consider a particle mass 'm' is confined in R one dim. Potential box of width L.

Given $V=0$, $0 < x < L$

$V=\infty$, $x < 0$, $x > L$



Schrodinger time independent eq^n of particle

$$\frac{d^2\psi}{dx^2} + \frac{2mE\psi}{\hbar^2} = 0$$ as $V=0$ inside the box

let $\frac{2mE}{\hbar^2} = k^2$ — (A)

$$\frac{d^2\psi}{dx^2} + k^2\psi = 0$$

Sol^n of above eq^n

$\psi = A \sin Kx + B \cos Kx$ — (B)

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To find the value of A and B we use boundary condition and normalise condition.

$$\psi = 0 \quad \text{at } x = 0 \quad (i)$$
$$\psi = 0 \quad \text{at } x = L \quad (ii)$$

Now apply the first boundary condition on eq^n B

$$0 = A\sin k(0) + \cos(0)\, x_0$$
$$0 = B$$

$\therefore$ $\psi = A \sin kx$

from (4)

$$0 = A \sin kL$$

A can't be zero so,

$$\sin kL = 0$$
$$kL = n\pi, \quad n \neq 0$$

$$\text{Or } k = \frac{n\pi}{L} \quad \text{---} \quad (5)$$

Put value of k in (I)

$$\frac{2mE}{\hbar^2} = \frac{n^2\pi^2}{L^2}$$

$$\text{or } E_n = \frac{n^2\pi^2\hbar^2}{2^2\, 2m}$$

E_n = eigen value

$$\int_{-\infty}^{\infty} (A \sin kx \cdot A \sin kx)\, dx = 1$$

$$\int_{0}^{L} (A \sin kx \cdot A \sin kx)\, dx = 1$$

$$A^2 \int_{0}^{L} \sin^2 kx \, dx = 1$$

$$\frac{A^2}{2} \times L = 1$$

$$A = \sqrt{\frac{2}{L}}$$

this is the eigen function of particle for each particle

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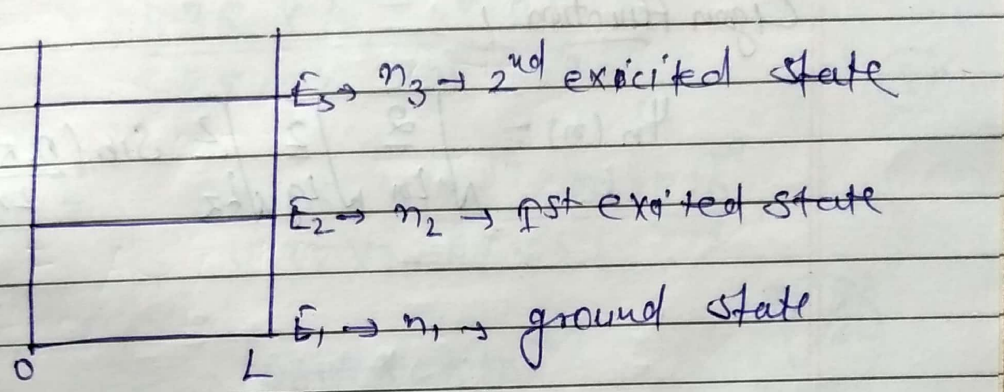
Eigen values:

$$E_n = \frac{n^2 h^2}{8mL^2} \quad \text{or} \quad \frac{n^2 \pi^2 \hbar^2}{2mL^2}$$

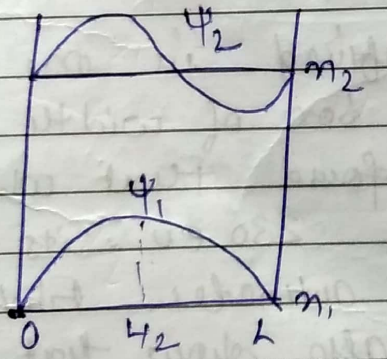
Eigen functions:

$$\psi_n = \sqrt{\frac{2}{L}} \sin\left(\frac{n\pi x}{L}\right)$$

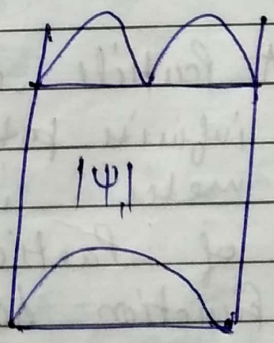
* Graphical representation of Eigen fn & Eigen values:



Eigen values



$|\psi_2|^2 \rightarrow$ Probability density $(\psi^* \psi)$



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Eigen function and eigen values of a particle of a 3D Potential box :

Sol^n :

Eigen value :

$$E_n = \frac{\hbar^2}{8m}\left[\frac{n_x^2}{L_x^2} + \frac{n_y^2}{L_y^2} + \frac{n_z^2}{L_z^2}\right]$$

Eigen Function :

$$\psi_n(x) = \sqrt{\frac{2}{L_x}}\sqrt{\frac{2}{L_y}}\sqrt{\frac{2}{L_z}} \sin\left(\frac{n_x \pi x}{L_x}\right) \sin\left(\frac{n_y \pi y}{L_y}\right) \sin\left(\frac{n_z \pi z}{L_z}\right)$$

Note : no. of nodes = $n-1$] exclude the exterior
no of antinodes = n] Points (end).

Q. A particle is confined in one dimen. infinite potential box of width of 0.2×10^{-9} meter. it is found that when Energy of Particle is 230 ev. its eigen function has 5 antinodes. Find the mass of Partic. also show that it can never have energy = 1 Kev

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Sol: width $= 0.2 \times 10^{-9}$

Energy $= 230$ eV $= 230 \times 1.6 \times 10^{-19} = 368 \times 10^{-19}$

anti nodes $= 5 = n$.

$m = ?$ $\quad E \neq 1$ KeV

$E = \frac{n^2 h^2}{8 m L^2}$ $\quad E = n^2 E_1$

$E = \frac{4.35 \times 10^{-67} \times 25}{8 \times m \times 0.2 \times 10^{-9}}$

$m = \frac{8 \times 368 \times 10^{-19} \times 0.2 \times 10^{-9}}{4.35 \times 10^{-67} \times 25}$

$= \frac{588.8 \times 10^{-28}}{108.75 \times 10^{-67}}$

$= 5.41 \times 10^{-31}$

$m = 9.32 \times 10^{-31}$

(1) $m = \frac{n^2 h^2}{8 E \times L^2} = 5 \times 4.39 \times 10^{-67}$

$E_1 = \frac{h^2}{8 m L^2}$

$= \frac{4.39 \times 10^{-67}}{8 \times 9.32 \times 10^{-31} \times (0.2 \times 10^{-9})^2}$

$E_1 = 1.47 \times 10^{-18}$

$E = n^2 E_1$

$n^2 = \frac{E}{E_1}$

$= 1.47$

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Q. An $e^{\ominus}$ is bound in 1D Potential box of width 2.5×10^{-10} m assuming the height of box to be infinite. calculate the lowest two (~~converted~~) energy value of $e^{\ominus}$

$$E = \frac{n^2 h^2}{8mL^2}$$

$$E_1 = \frac{h^2}{8mL^2}$$

$$E_2 = \frac{4h^2}{8mL^2}$$

$$E_1 = \frac{(6.63 \times 10^{-34})^2}{8 \times 9.1 \times 10^{-31} \times (2.5 \times 10^{-10})}$$

$$= \frac{4.39 \times 10^{-67}}{182 \times 10^{-41}} = \frac{2.41 \times 10^{-67}}{10^{-41}}$$

$$8 \times 9.1 \times 10^{-31} \times 6.25 \times 10^{-20}$$

$$E_1 = 2.41 \times 10^{-20}$$

$$E_2 = 4.82 \times 10^{-20}$$

$$= \frac{4.39 \times 10^{-67}}{485 \times 10^{-51}} =$$

$$E_1 = 9.6 \times 10^{-19}$$

$$E_2 = 4 \times \text{[illegible]} = 38.4 \times 10^{-19}$$

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(3) Calculate the Energy diff b/w the ground state and first excited state for an electron in one dim. box of length 10^{-8} cm

$10^{-8} \times 10^{-2}$

10^{-10}

$$E_1 = \frac{n^2}{8mL^2}$$

$$= \frac{(6.63 \times 10^{-34})^2}{8 \times 9.1 \times 10^{-31} \times (10^{-10})^2}$$

$E_1 = 38$ eV
$E_2 = 114$ eV

$$= \frac{(6.63 \times 10^{-34})^2}{8 \times 9.1 \times 10^{-31} \times 10^{-20}}$$

$$= \frac{4.39 \times 10^{-67}}{72.8 \times 10^{-51}} = 0.06 \times 10^{-16}$$

$$= 0.06 \times 10^{-16}$$

$\frac{6.03}{\times 10^{-18}}$

0.018

$\frac{n^2h^2}{8mL^2} = \frac{p^2}{2m}$

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Q an $e^{\ominus}$ is confined to move b/w two rigid walls separated by 10^{-9} m. Find the de-Broglie wave length the resulting representing wave first 3 allowed energy states at the corresponding Energies

$$L = 10^{-9} m$$
$$m = 9.1 \times 10^{-31} kg$$

$$\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{h}{\sqrt{2mE}}$$

$$E = \frac{h^2 n^2}{8mL^2}$$

Method → $\lambda_1 = \frac{2L}{n}$

$$\lambda_1 = \frac{2 \times 10^{-9}}{1} = 2 \times 10^{-9}$$

$$\lambda_2 = \frac{2}{2} \times 10^{-9} = 1 \times 10^{-9}$$

$$\lambda_3 = \frac{2}{3} \times 10^{-9} = 0.67 \times 10^{-9}$$

$E = \frac{p^2}{2m}$

$$p_1 = \frac{h}{\lambda} = \frac{6.63 \times 10^{-34}}{2 \times 10^{-9}}$$

Probability

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Q A Particle is moving in 1 D Potential Box of width 25 A° Calculate the Probability of finding the Particle with in an interval of 5 A° at the center of box where it is in its lowest Energy state

Ans = 0.4 Probability = $\psi^*(x)\,\psi(x)$

$= \sqrt{\frac{2}{L}} \sin\left(\frac{n\pi x}{L}\right) \cdot \sqrt{\frac{2}{L}} \sin\left(\frac{n\pi x}{L}\right)$

$x = \frac{2.5}{2}$

P. Δn

$$\lambda = \frac{2L}{n}$$

Unit - 2

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Free electron Theory :

- Classical free electron theory
- Quantum free $e^{\ominus}$ theory
- Band theory

Classical free e^- theory :

It is developed by Drude & Lorentz in 1900

It is Based on the assumtion that free electron obeys the classical Mechanics Law

It not give the value of specific heat of Semiconductor materials.

It also not explain the electrical and

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(3) Band theory / Zone theory :-

(1) It is devised by Bloch in 1928
(2) It is based on the assumption that e^- moves in a periodic Potential provided by Lattice.
(3) It explain almost all the physical Property of material.
(4) It completely explain the mech^n of Semi-conductor and Insulator.

* Postulates of classical free $e^\ominus$ theory :-

1. The valence e^- of metallic atoms are free to move about the hole volume of the metals.
2. These free e^- are moving randomly in any direction and make collision with Positive ions fixed in the lattice or other free electrons. As this collision is elastic so, there is no loss of energy.
3. The moment of free e^- obeys the laws of Classical kinetic theory of gasses
4. Velocity of free e^- inside the metal obeys the maxwell boltzmann distribution Law.
5. The free e^- are moving randomly in a constant Potential field due to Positive ions fixed in the lattice but in a Particular direction the velocity of free e^- is zero.

$I = neAv_d$

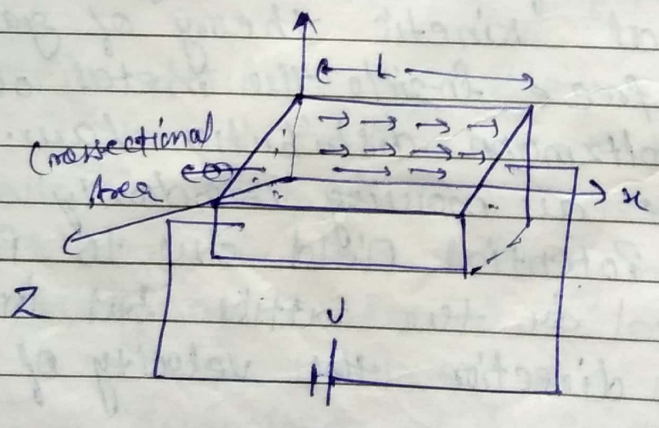
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6. When an electric field is applied to the metal the free e^- slightly modified there random motion and slowely get drifted in a direction opposite to the applied electric field. and aquire additional velocity which is called drift velocity

7. In absence of electric field distance travell b/w two collission is called mean free path and denoted by (λ). and time taken by an e^- b/w two successive collission are known as mean free time and collision time and denoted by (τ).
Average velocity of free $\bar{e}$ is called V_{rms} velocity also known as thermal velocity

8. In this model it is assume that
Collission time = Relaration time and
thermal velocity = drift velocity

* Electrical Conductiwity of metal (σ):
Let us assume



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Let us consider a piece of metal whose length is L and area A a voltage (V) is applied around the cross sectional area of metal

$$E = \frac{V}{L} \Rightarrow V = EL$$

$$V \propto I \qquad V = IR$$

$$I = V/R$$

$$I = \frac{El}{R} \qquad R = \frac{\rho l}{A}$$

$$I = \frac{El \times A}{\rho l} = \frac{E \times A}{\rho}$$

$$\frac{I}{A} = \frac{E}{\rho}$$

$$J = \frac{I}{A} = \frac{E}{\rho} \quad \text{as} \quad \sigma = \frac{1}{\rho}$$

then

$$\boxed{J = \sigma E}$$ ohm Law

If n is the concentration of e^- in the metal then total no. of e^- in metal

$$= nAXL$$

then the total charge present in metal

$$Q = -nAL \times e \quad \text{---} (1)$$

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the time taken by e in the metal is

$$t = \frac{l}{v_d} \quad - (2)$$

Then current flowing in the metal is given by

$$I = \frac{Q}{t} = - \frac{nAle \times v_d}{l}$$

$$\boxed{I = -neAv_d}$$

$$\frac{I}{A} = -nev_d$$

$$\boxed{J = -nev_d} \quad - (A)$$

Value of v_d is determine by using the condition of steady state acc. to which

Velocity loss during collision = velocity gain by applied Electric field

if at $t = 0$

v_0 is the velocity of an e^-

then in absence of E.F

$$\langle v_0 \rangle = 0$$

Final
When E.F is applied the velocity of $e^\ominus$ is v_f then after time t is equat to τ

$$t = \tau$$

$$v_f = v_0 + a \cdot \tau$$

then average value of v_f = avg. value of $v_0 + a\tau$

$$\langle v_f \rangle = \langle v_0 \rangle + a\tau$$

$$v_f = a\tau$$

$$v_d = a\tau \quad \text{——— (3)}$$

To Calculate the value of a using the condition as

$$F = -eE$$

$$Ma = -eE$$

$$a = -\frac{eE}{m}$$ Sub in eq^n (3)

(4)

$$\boxed{v_d = -\frac{eE}{m}\cdot\tau} \quad \text{- B}$$

Now, Sub the value v_d in A eq^n.

$$\boxed{J = \frac{ne^2\tau E}{m}}$$

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as $J = \sigma E$

$\sigma E = \frac{ne^2\tau}{m} E$

$$\boxed{\sigma = \frac{ne^2\tau}{m}} \quad (c)$$

$$\boxed{\rho = \frac{1}{\sigma}}$$

It shows that the conductivity of any metal depends on the collision time and collision time depends on the temp. So, resistivity and conductivity is also depends on temp.

The Conductivity in terms of temp.:

as $\lambda = V_{rms} \cdot \tau$

$\lambda \rightarrow$ mean free path.

It is the avg. dist. travell by an e^- b/w any two successive collision

$$\tau = \frac{\lambda}{V_{rms}} \quad (5)$$

As acc. to classical theory when metal is an a state of absolute temp. of t. then K.E of e^- is given by

$$\boxed{E_K = \frac{3}{2} k_B T}$$

Case-1

Semi → T

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$$\frac{1}{2}mv_{rms}^2 = \frac{3}{2}K_B T$$

$$V_{rms} = \sqrt{\frac{3K_B T}{M}}$$ Substitute the eq^n in (5)

$$\boxed{\tau = \frac{\lambda}{\sqrt{\frac{3K_B T}{M}}}} \quad \text{(6)}$$

Sub the value of τ in c eq^n

$$\sigma = \frac{ne^2}{m} \times \frac{\lambda}{\sqrt{\frac{3K_B T}{M}}}$$

$$\boxed{\sigma = \frac{ne^2\lambda}{\sqrt{3MK_B T}}}$$

Final eq^n of electrical Conductivity.

Case-1

As temp. increase the Conductivity decreases the reason is as by increasing the temp. thermal energy provide the energy to all e^- to vibrate from their eqb position and they start to interact with Bound e^- as well as Scattered e^-.

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(2) As for long mean free path & conductivity is high it is due to less no. of $e^{\ominus}$ collides with the other $e^{\ominus}$ in the atom

1. A uniform silver wire has resistivity of 1.45×10^{-8} Ωm at room temp. for an electric field along the wire of 1 V/cm compute the average V_d of an $e^{\ominus}$ assuming that there are 5.8×10^{28} conduction $e^{\ominus}$ /m³ also calculate the mobility and average collision time of $e^{\ominus}$

$$I = nAeV_d$$

$$V_d = \frac{I}{neA}$$

$$V_d = \frac{eE}{m}\tau$$

$$\sigma E = \frac{ne^2\tau E}{m}$$

$$\tau = \frac{m}{\sigma ne^2}$$

$$\mu = ?$$

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$\rho = 1.45 \times 10^{-8}\ \Omega m$

$n = 5.8 \times 10^{28}\ /m^3$

$E = 1\ V/cm = 100\ V/m$

$\mu = ?$ $\tau = ?$

$$\tau = \frac{m}{ne^2\rho}$$

$$= \frac{9.1 \times 10^{-31}}{5.8 \times 10^{28}(1.6 \times 10^{-19})^2 \times 1.45 \times 10^{-8}}$$

$$= \frac{9.1 \times 10^{-31}}{2.56 \times 10^{-32} \times 21.52 \times 10^{-8}}$$

$$= 0.42 \times 10^{-17} = 4.22 \times 10^{-14}\ sec$$

$$\mu = \frac{\sigma}{ne} = \frac{1}{\rho ne}$$

$$= \frac{1}{1.45 \times 10^{-8} \times 5.8 \times 10^{28} \times 1.6 \times 10^{-19}}$$

$$= \frac{1}{13.45 \times 10^{1}} = \frac{1}{134.5} =$$

$$= 7.43 \times 10^{-3}\ m^2/V sec.$$

$$V_d = \mu \times E$$

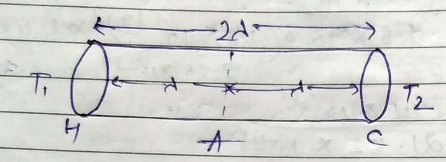
$$= 7.42 \times 10^{-3} \times 100 = 0.742\ m/s$$

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* Thermal Conductivity in metal :

Thermal energy is transfer by two Mech^{n}

- Transfer of free e^-
- Lattice vibration (Phonons)



$\lambda \rightarrow$ mean free path of e^-

$T_1 \Rightarrow$ temp of Hot end H.
$T_2 \Rightarrow$ " " Cold " C

$2d \rightarrow$ distance b/w H & C
$d \rightarrow$ " of both end from
A is at centre of tube, $d \rightarrow$ H A & AC

Amount of heat transfer from hot end (H) to cold end (C)

Q. $\propto$ Area of face A
$\propto$ temp. gradient b/w H & C $\left[\frac{T_1 - T_2}{2d}\right]$
$\propto$ time of flow (t)

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$$Q = \frac{KA(T_1 - T_2)t}{2d} \quad \text{---} \quad (A)$$

K = quantity of heat transmitted
or
Coefficient of thermal Conductivity

$$K = \frac{2Qd}{A(T_1 - T_2)t} \quad \text{---} \quad (B)$$

unit - W/m K.
watt/meter kelvin.

As temp. at H is higher than C.
average K.E of e^- at $H = \frac{3}{2} K_B T_1$

Similarly

average K.E of e^- at $C = \frac{3}{2} K_B T_2$

Let n = no. of Conduction e^- in metal
v = root mean square velocity of e^-

If we assume that there are equal Probability for e^- to move in all the 6 direction so on.

average of $\frac{1}{6}n$ e^- can travel in any direction.

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So, no. of $\bar{e}$ crossing / area / time at point A $= \frac{1}{6} n_1 v$

Now,

heat energy transferred / area / time from H → C

= no. of e^- crossing point A × average K.E of $\bar{e}$ moving from H → C

So, $Q_H = \frac{1}{6} nv \times \frac{3}{2} K_B T_1$

$= \frac{1}{4} n v K_B T_1$ — (a)

the energy transferred / area / time from C → H

$Q_c = \frac{1}{4} n v K_B T_2$ — (b)

Heat energy transferred / area / time from across point A / sec

$Q = Q_H - Q_C$

$Q = \frac{1}{4} n v K_B (T_1 - T_2)$ — (c)

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Substitute Q from eq^{n} (A) → (C)

$$\frac{K(T_1 - T_2)}{2A} = \frac{1}{4} n v K_B (T_1 - T_2)$$

$A = 1, \; t = 1$

$$K = \frac{1}{2} n v K_B \lambda \quad \text{---} \quad (D)$$

Now, From classical free e theory the electronic specific heat capacity of metal

$$C_e = \frac{3}{2} R \qquad \text{as } R = n K_B$$

$$C_e = \frac{3}{2} n K_B$$

$$\frac{2C_e}{3} = n K_B$$

Substitute $n K_B$ in eq. (D)

(R) $K = \frac{1}{3} C_e v \lambda$

$$K = \frac{1}{2} n v K_B \lambda$$

$$K = \frac{1 v \lambda 2 C_e}{2 \times 3} = \frac{C_e \lambda v}{3}$$

(E)

$K = \frac{1}{2} \times$

It shows thermal conductivity

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In terms of electronic specific heat K is cal. either by eq (1) & (2)

* Wiedemann - Franz law:

Acc. to this law, ratio of thermal conductivity (K) to electrical conductivity (σ) is proportional to temp. (T) for a large no. of metal

$$\frac{K}{\sigma} \propto T$$

$$\frac{K}{\sigma T} = L \quad \text{---} \quad (1)$$

L = Proportionality Constant known as Lorentz no.

L = Lorentz no = 2.44×10^{-8} watt-ohm/K^2 at 0°C

2.93×10^{-8} at 100°C (experimental value)

as

$$K = \frac{1}{2} m v k_B$$

$$\sigma = \frac{ne^2\tau}{m}$$

Always Cherish

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So, $\frac{K}{\sigma} = \frac{1/2\, m v K_B}{\frac{n e^2 \tau}{m}}$

$= \frac{m v K_B}{2 e^2 \tau} = \frac{1}{2} m^2 v K_B$

as $\lambda = v\tau$

$\frac{K}{\sigma} = \frac{m v^2 K_B}{2e^2}$

K.E of $e^- = 1/2 m v^2 = 3/2 K_B T$

$\frac{K}{\sigma} = \frac{3}{2} K_B T \times \frac{K_B}{e^2}$

$\frac{K}{\sigma} = \frac{3}{2}\left(\frac{K_B}{e}\right)^2 T.$

$L = \frac{K}{\sigma T} = \frac{3}{2}\left(\frac{K_B}{e}\right)^2$

$L = \frac{K}{\sigma T} = \frac{3}{2}\left(\frac{1.38 \times 10^{-23}}{1.6 \times 10^{-19}}\right)^2$

$L = \frac{3}{2}\left(\frac{1.38 \times 10^{-23}}{1.6 \times 10^{-19}}\right)^2$

$= 1.11 \times 10^{8}$ ohm $W-2/K2$

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This value of Lorentz no. is half ½ of experimental value of Lorentz no. and this discrepancy in theoretical value can be rectified by using quantum theory.

Now, acc. to Quantum theory, thermal conductivity in metals is modified by considering the electron specific heat and given by

$$K = \frac{n\pi^2 k_B^2 T\tau}{3m}$$

So,

$$L = \frac{K}{\sigma T}$$

$$L = \frac{\frac{n\pi^2 k_B^2 T\tau}{3m}}{\frac{ne^2\tau T}{m}}$$

$$L = \frac{\pi^2}{3} \times \left(\frac{k_B}{e}\right)^2$$

$$= \frac{\pi^2}{3} \times \left(\frac{1.38 \times 10^{-23}}{1.6 \times 10^{-19}}\right)^2$$

$$L = 2.447 \times 10^{-8}\ \omega^{-2}/K^2$$

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Qu: A copper wire of length 0.5 m and Diameter 0.35 mm Have the Resistance of 0.09 Ω at 20°C. if the thermal conductivity of Copper at 20°C is 390 watt/m K Calculate the Lorentz no. Also Compare the this value with value predicted by classical free electron theory.

Sol: $l = 0.5m$

diameter $= 0.35\,mm = 0.35 \times 10^{-3}$

$R = 0.09\,\Omega$ at $20°C \rightarrow T = (273+20) = K$

$K = 390$ w/mK

$L = ?$

& Compare the value of L with Classical theory.

$$L = \frac{K}{\sigma T}$$

$R = \frac{\rho l}{A}$

$\rho = \frac{RA}{l}$

$\sigma = \frac{l}{RA}$

$$\sigma = \frac{l}{RA} = \frac{0.5}{0.09 \times 0.35 \times 10^{-3}}$$

$$= \frac{0.5}{0.09 \times 0.35} \times 10^{3}$$

$$\sigma = \frac{l}{RA} = \frac{0.5}{0.09 \times \left(\frac{0.35}{2} \times 10^{-3}\right)^2 \times \pi}$$

$$\sigma = 5.78 \times 10^{7} \text{ /Ω.m}$$

$$L = \frac{K}{\sigma T} = \frac{390}{5.78 \times 10^{7} \times 293} =$$

$$= 0.23 \times 10^{-7} \text{ watt/K}$$

$$= 2.3 \times 10^{-8} \text{ watt/K}$$

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Classical value = 1.11×10^{-8}

The classical value is 1.11×10^{-8} Watt Ω/K which shows that @ classical value is half of this value

Q. Calculate the drift velocity and thermal velocity of condiction $e^{\ominus}$s in copper at a temp. of 300 K when copper wire of length 2m and Resistance = 0.02 Ω carries the current of 15A. and μ (mobility) = 4.3×10^{-3} m²/Vs

~~L = 2m~~

T = 300 K

$$I = nAeV_d$$

$$V_d = \frac{I}{neA} = \frac{15}{1 \times 1.6 \times 10^{-19} \times}$$

$V_d = \mu E$ $\left[E = \frac{V}{l}\right]$

$= 4.3 \times 10^{-3} \times 0.15$ $E = \frac{IR}{l}$

$= 0.64 \times 10^{-3}$ m/s $= \frac{15 \times 0.02}{2}$

$= 0.01 \times 15$

$= 0.15$

$$v = \sqrt{\frac{3K_BT}{m}} = \sqrt{\frac{3 \times 300 \times}{9.1 \times 10^{-31}}}$$

$K_B = 1.38 \times 10^{-23}$

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$$\sqrt{\frac{900 \times 1.38 \times 10^{-23}}{9.1 \times 10^{-31}}}$$

$-23+31$
8

$$\sqrt{136.4 \times 10^{-8}}$$

$$= 1.16 \times 10^{-4}\ m/s$$

(14) $V_p = \left(\frac{2\pi S}{\rho \lambda}\right)^{1/2}$

$$V_g = V_p - \lambda \frac{dV_p}{d\lambda}$$

(15) $\frac{p^2}{2m} = E$

$E = 15\ KeV$ $\quad p = \sqrt{2mE}$

$\Delta p \cdot \Delta x = \hbar/2$

$\Delta p = \frac{\hbar}{\Delta x} = \frac{\Delta p}{p} \times 100$

Ans:

(B) $\frac{h}{p} = \frac{hc}{E} =$ $\quad \frac{1}{p} = \frac{c}{E}$

$$p = \frac{E}{c}$$

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(b) $E^2 = p^2c^2 + m_0^2c^4$

$E^2 = p^2c^2$

$E = pc$

used only photon.

Energy of photon $= E = pc = \frac{hc}{\lambda}$

only photon moves velocity of light.

** Electron doesn't exist in Nucleus

Lorentz → classical quantum

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22/09/18

* Draw backs of classical free e theory :-

1. Theoretical value of specific heat capacity does not match with the experimentally observed value.

2. At low temp., the electrical Conductivity (σ) and thermal Conductivity (K) vary in different ways. Therefore,

   K/σT is not constant at these temp., but acc. to classical free e theory it is constant.

3. Classical theory states that e absorb the supplied energy, but quantum state that only few electrons absorb the supplied energy.

4. The concept of compton effect, black body radiation cannot be explained on this basic of classical theory.

5. Ferromagnetism cannot be explained by this theory.

Energy → not

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* Quantum free e⁻ theory :-

(1) It was developed by Sommerfeld's in 1928

(2) It follows the de-Broglie hypothesis of matter waves and schrodinger matter wave eq⁴.

(3) It based on Fermi-Dirac Statistics of e⁻ distribution

(4) Potential energy of an e⁻ is periodic. Free e⁻ find themselves in a potential which is constant every where inside the metal but outside is very high.

(5) In metal, energy levels are filled in accordance with Pauli's exclusion Principle

Fermi-Dirac ~~stat~~ Distribution function (also known as occupation probability)

(1) In quantum free e⁻ theory e⁻ are distributed among the various quantum State at any given temperature according to Fermi-Dirac dist. function

The following consideration are used in the development of the statistics

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$e^{-\infty} = 0$
$e^{\infty} = \infty$

1) Indistinguishability of the electron.

2) Electron wave nature.

3) The Pauli exclusion Principle

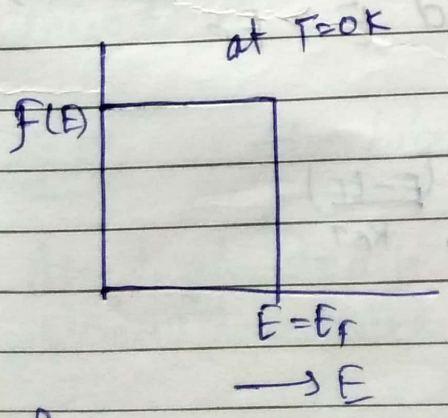
According to which:

The probability that a particular state E is occupied by an electron is given by.

$$f(E) = \frac{1}{1 + e^{\frac{(E - E_f)}{K_B T}}} \quad \text{— (A)}$$

f(E) = Probability that a orbit of Energy E is populated in an ideal e^- gas in thermal eq^b.

K_B = Boltzmann constant (1.38×10^{-23} J/K)
T = Absolute temperature.
E_f = Fermi energy or Fermi level.



Fermi f^n at 0K.



at T=0 dist. of $e^{\ominus}$

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Effect of temp. on fermi function :

Case : I At absolute zero ($T = 0K$) & $E < E_f$

$$f(E) = \frac{1}{1 + e^{\frac{(E - E_f)}{K_B T}}}$$

$$f(E) = \frac{1}{1 + e^{\left(\frac{E - E_f}{K_B 0}\right)}}$$

$$f(E) = \frac{1}{1 + e^{-\infty}}$$

$$f(E) = 1 .$$

i.e. all the Energy level below the E_f are fully occupied by e^- that is there 100% Probability of finding an electron below the fermi Energy level.

Case : II

At absolute zero ($T = 0K$) and $E > E_f$

$$f(E) = \frac{1}{1 + e^{\frac{(E - E_f)}{K_B T}}}$$

$$f(E) =$$

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$$f(E) = \frac{1}{1+\infty} = \frac{1}{\infty}$$

$$f(E) = 0$$

- Energy levels above the E_f is not occupied by e^- i.e 0%. Probability of finding the e^- above the fermi Energy level at $T = 0K$

Case = III

At absolute zero ($T > 0K$) & $E = E_f$

$$f(E) = \frac{1}{1+e^{\frac{(E-E_f)}{K_B T}}}$$

$$f(E) = \frac{1}{1+e^0} = \frac{1}{1+1} = \frac{1}{2}$$

$$f(E) = 0.5$$

At temp. above 0k, ie at room temp & $E = E_f$ only 50 % Probability for an e^- to occupy fermi energy level.

Case : IV At high temp. $K_B T >> E_f$

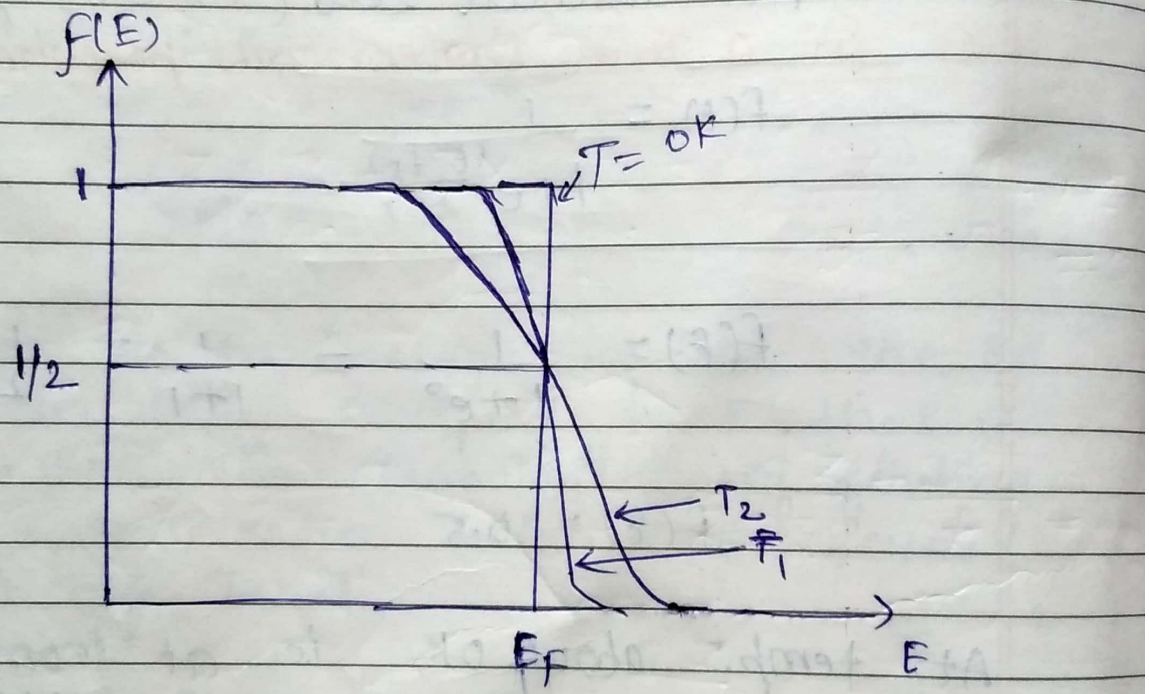
At high temp. e^- are excited to vacant level above fermi energy

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level, i.e Probability of finding the e⁻ above E_f become greater then zero.

→ at high temp. e⁻ lose their quantum mechinical character and obeys the Boltzmann dist. fⁿ.

→ At high temp. both quantum & classical Statistic give similar result.



Fermi - Dirac distribution fⁿ at diff. temp.

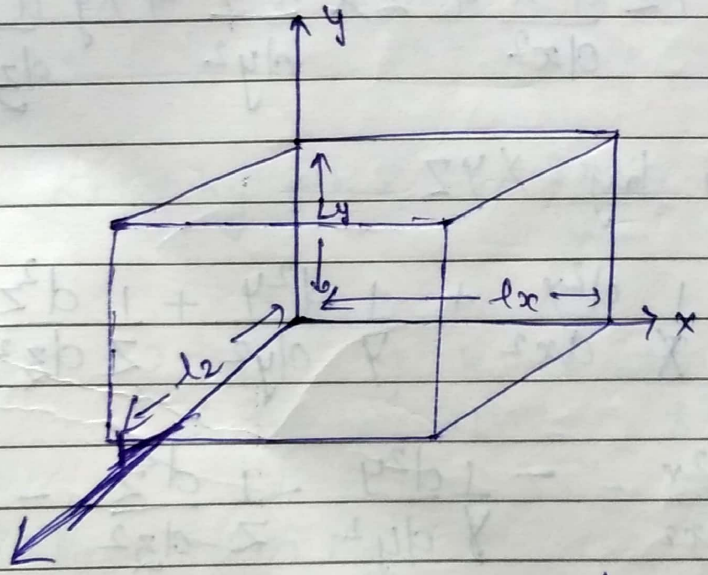
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* Quantum free e theory :

Acc. to quantum free e theory e's have discrete energy states in a metal and this ~~discreate~~ energy state are chaaterised by quantum no.

In quantum free e theory moment of e inside the metal can be consider as moment of an e in a 3D Potential box.

* e in a Three Dimentional potential box :



lx, ly, lz are length of box in x, y, z dir.

$V = 0 \quad 0 < x < l_x$

$= 0 \quad 0 < y < l_y$

$= 0 \quad 0 < z < l_z$

imp: 10 Marks

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Schrodinger time independent eq^n for e$^-$ inside the box: 3D

$$\nabla^2\psi + \frac{2m}{\hbar^2} E\psi = 0$$

$$\frac{d^2\psi}{dx^2} + \frac{d^2\psi}{dy^2} + \frac{d^2\psi}{dz^2} + \frac{2m}{\hbar^2} E\psi(x,y,z) = 0 \quad \text{---(1)}$$

$$\psi(x,y,z) = X(x)\,Y(x)\,Z(z)$$

it Satisfy the eq^n (1)

$$YZ\frac{d^2X}{dx^2} + ZX\frac{d^2Y}{dy^2} + XY\frac{d^2Z}{dz^2} + \frac{2mE}{\hbar}XYZ = 0$$

divide by XYZ

$$\frac{1}{X}\frac{d^2X}{dx^2} + \frac{1}{Y}\frac{d^2Y}{dy^2} + \frac{1}{Z}\frac{d^2Z}{dz^2} + \frac{2mE}{\hbar} = 0$$

$$\frac{1}{X}\frac{d^2X}{dx^2} = -\frac{1}{Y}\frac{d^2Y}{dy^2} - \frac{1}{Z}\frac{d^2Z}{dz^2} - \frac{2mE}{\hbar^2}$$

let $\frac{1}{X}\frac{d^2X}{dx^2} = k_x$ — (a)

$$-\frac{1}{Y}\frac{d^2Y}{dy^2} - \frac{1}{Z}\frac{d^2Z}{dz^2} - \frac{2mE}{\hbar} = k_x$$

WAVE FUNCTION GENERALLY

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$$\frac{1}{Y}\frac{d^2y}{dy^2} = -\frac{1}{Z}\frac{d^2z}{dz^2} - \frac{2mE}{\hbar^2} - K_x$$

Let $\frac{1}{y}\frac{d^2y}{dy^2} = K_y$ — (b)

$$-K_x - \frac{1}{z}\frac{d^2z}{dz^2} - \frac{2mE}{\hbar^2} = K_y$$

$$\frac{1}{z}\frac{d^2z}{dz^2} = -K_x - K_y - \frac{2mE}{\hbar^2}$$

Let $\frac{1}{z}\frac{d^2z}{dz^2} = K_z$. — (c)

$$-K_x - K_y - \frac{2mE}{\hbar^2} = K_z$$

$$K_x + K_y + K_z = -\frac{2mE}{\hbar^2}$$ — (2)

$$K_x = -\frac{2mE_x}{\hbar^2} \; ; \; K_y = -\frac{2mE_y}{\hbar^2}$$

$$K_z = -\frac{2mE_z}{\hbar^2}$$

By Solving (a)

$$\frac{1}{x}\frac{d^2x}{dx^2} = K_x$$

$$\frac{d^2x}{dx^2} - K_x X = 0$$

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$X(x) = A \sin [Bx + C]$

where A, B and C are constants

A is calculate by using the Normalised cond'

B and C calculate by using the Boundry condition of wave function.

Boundry condition

(i) $X = 0$, $x = 0$

(ii) $X = 0$, $x = lx$

by (i) boundry condition.

$A \neq 0$

$0 = A \sin [B \cdot 0 + C]$

$\sin C = 0$

$C = 0$

$X(x) = A \sin Bx$

by (ii) boundary condition.

$0 = A \sin Blx$

$A \neq 0$

$\sin Blx = 0$

$n \neq 0$

$Blx = n\pi$ $\quad n = 1, 2, 3 \ldots$

$B = \frac{n\pi}{lx}$ $\quad n \neq 0$, $n = 1, 2, 3 \ldots$

$X(x) = A \sin \left(\frac{n\pi x}{lx}\right)$

SOLVE

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use the normalsised condition :-

$$\int_0^{l_x} X(n) \cdot X^*(n)\, dx = 1$$

$$A^2 \int_0^{l_x} \left[\sin^2\left(\frac{n\pi}{l_x}\right) x \right] dx = 1$$

$$A^2 \int_0^{l_n} \left[\frac{1 - \left(\cos\frac{2n\pi}{l_n}\right)x}{2} \right] dx = 1$$

$$\frac{A^2}{2} \left[x - \right.$$

$$= \frac{A^2}{2} \left[x - \frac{l_n}{2n\pi} \sin\left(\frac{2n\pi x}{l_x}\right) \right]_0^{l_n} = 1$$

$$\frac{A^2}{2} \left[l_x - 0 \right] = 1$$

$$A^2 = \frac{2}{l_x} \Rightarrow A = \sqrt{\frac{2}{l_x}}$$

$$X(n) = \sqrt{\frac{2}{l_x}} \sin\left(\frac{n\pi}{l_n}\right) x \quad \text{— (A)}$$

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Similarly by using eqn (b) and (c) we get

$$Y_{(y)} = \sqrt{\frac{2}{l_y}} \sin\left(\frac{n\pi}{l_y}\right) y$$

$$Z_{(z)} = \sqrt{\frac{2}{l_z}} \sin\left(\frac{n\pi}{l_z}\right) z$$

and

$$\psi = X_{(x)} \cdot Y_{(y)} \cdot Z_{(z)}$$

$$= \left[\sqrt{\frac{2}{l_x}}\sqrt{\frac{2}{l_y}}\sqrt{\frac{2}{l_z}} \sin\left(\frac{n\pi}{l_x}\right)x \cdot \sin\left(\frac{n\pi}{l_y}\right)y \cdot \sin\frac{n\pi z}{l_z}\right]$$

For Eigen Value or Energy Values.

$$X_{(x)} = \sqrt{\frac{2}{l_n}} \sin\left(\frac{n\pi}{l_x}\right)x \quad \text{(A)}$$

$$\frac{d^2X}{dx^2} - KX = 0$$

diff eqn (A) twice w.r.t x.

$$\frac{dX_{(x)}}{dx} = \sqrt{\frac{2}{l_x}} \left(\frac{n\pi}{l_x}\right) \cos\left(\frac{n\pi}{l_x}\right)x$$

calculate Prob → fermi dirac

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Substitute.

again differentiate

$$\frac{d^2\psi}{dx^2} = -\sqrt{\frac{2}{l_x}}\left(\frac{n\pi}{l_n}\right)^2 \sin\left(\frac{n\pi}{l_n}\right)x$$

$$\frac{d^2X}{dx^2} + \left(\frac{n\pi}{l_n}\right)^2 \cdot X_{(x)} = 0$$

$$K = \left(\frac{n\pi}{lx}\right)^2 \Rightarrow K = \frac{-n^2\pi^2}{l_x^2} \quad (B)$$

Now substitute the value of K from (B) to (2)

$$K_x + K_y + K_z = -\frac{2mE}{\hbar^2}$$

$$+\left[\frac{n^2\pi^2}{lx^2} + \frac{n^2\pi^2}{ly^2} + \frac{n^2\pi^2}{lz^2}\right] = +\frac{2mE}{\hbar^2}$$

$$E = \frac{\hbar^2\pi^2}{2m}\left[\frac{n_x^2}{l_x^2} + \frac{n_y^2}{l_y^2} + \frac{n_z^2}{l_z^2}\right]$$

This is the complete eigen value of $e^{\ominus}$ in a 3D Potential box

→ Density of States

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which shows that ~~each~~ each energy state has a quantum no and diff eigen function.

It also represent the motion of $e^{\ominus}$ inside the metal in different quantum state.

(21)

* Density of States : N(E) ⇒
It is denoted by $\dot{N}(E)$

It is used to find the no. of states per unit volume in energy range b/w E and E+dE

and its unit is $/m^3 kvolt$ or $/m^3 ev$

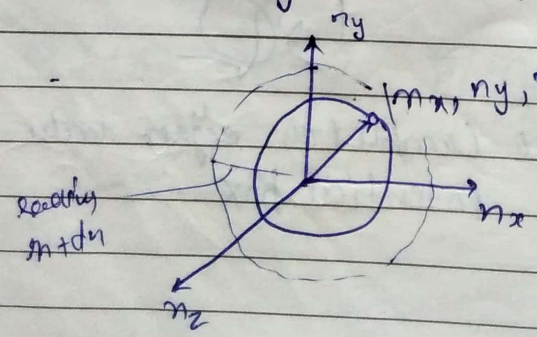
let us consider three dimenssional space with coordinates n_x, n_y and n_z

In this coordinate system, there is vector n whose value is $n^2 = n_x^2 + n_y^2 + n_z^2$

↓

magnitude at a point

The



$E = \frac{n^2 h^2}{8 m L^2}$

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The each point of this sphere is correspond to a unit cubical cell.

So, the total no. of points inside the sphere is equal to volume of sphere

$$= \frac{4}{3} \pi n^3$$

The energy state available in one octant of this sphere is equal to

$$= \frac{1}{8} \times \frac{4}{3} \times \pi n^3 \qquad n \neq 0, \; n > 0$$

Energy state with in one octant of sphere of radius $= (n + dn)$

and Energy $= E + dE$

Energy state of octant of the sphere of radius $(n+dn)$ & energy $(E+dE)$

$$= \frac{1}{8} \times \frac{4}{3} \pi (n+dn)^3$$

Now the energy state available b/w

$$E \text{ \& } E+dE = \left[\frac{1}{8} \times \frac{4}{3} \pi \left[(n+dn)^3 - n^3 \right] \right]$$

$N(E) =$

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$$N(E) = \frac{1}{6}\pi\left[n^3 + dn^3 + 3n^2\,dn + 3n\,dn^2 - n^3\right]$$

$$N(E) = \frac{\pi}{6} \times 3n^2\,dn \qquad \left[\text{neglect higher order of } dn\right]$$

$$N(E) = \frac{\pi}{2} \times n^2\,dn \quad - (1)$$

Now let us suppose e^- is confined in a cubical metal piece of size a.

then acc. to quantum theory the energy of $e^\ominus = E = \frac{n^2 h^2}{8ma^2}$

$$n^2 = \frac{8ma^2E}{h^2}$$

differentiate

$$2n\,dn = \frac{8ma^2\,dE}{h^2}$$

Now substitute the value of n & dn in eq^n (1)

$$N(E) = \frac{\pi}{2} \times \left(\frac{8ma^2E}{h^2}\right)^{1/2} \times \frac{8ma^2}{2h^2}\,dE$$

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$$= \frac{\pi}{4}\left(\frac{8ma^2}{h^2}\right)^{3/2} E^{1/2}\, dE$$

$$= \frac{\pi}{4}\frac{a^3}{h^3} \cdot 2^3 (2m)^{3/2} E^{1/2}\, dE$$

$$N(E) = 2\pi \frac{a^3}{h^3} (2m)^{3/2} E^{1/2}\, dE$$ Learn

Acc. to Pauli's exclusion principle in a one energy state there are two e⊖'s which can occupied the energy state one with spin up and one with spin down

so, the total no. of Energy state = $2N(E)$

Energy ~~denisty~~ density b/w E & $E+dE$

$$N(E)dE = \frac{4\pi}{h^3} \cdot a^3 (2m)^{3/2} E^{1/2} \cdot dE$$ Learn

if ~~For~~ cubical metal
$a = 1 \quad a^3 = 1$

$$N(E)dE = \frac{4\pi}{h^3} (2m)^{3/2} E^{1/2}\, dE$$

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Carrier concentration in terms of fermi energy: denote (n_e)

n_e = no. of e^- per unit volume in the energy interval $E+dE$

$$n_e = \int N(E) F(E)\, dE$$

Substitute the value of $N(E)$ and $F(E)$

$$n_e = \int \frac{4\pi}{h^3} (2m)^{3/2} E^{1/2} \times \frac{1}{1+e^{(E-E_F)/K_BT}}\, dE$$

below fermi Energy State ⇒ Energy state completely occupied

At $t=0K$, $F(E)=1$

$$n_e = \int \frac{4\pi}{h^3} (2m)^{3/2} E^{1/2}\, dE$$

$$n_e = \int_0^{E_f} \frac{4\pi}{h^3} (2m)^{3/2} E^{1/2}\, dE$$

$$n_e = \frac{4\pi}{h^3} (2m)^{3/2} \int_0^{E_f} E^{1/2}\, dE$$

$$n_e = \frac{4\pi}{h^3} (2m)^{3/2} \left[\frac{2}{3} E^{3/2}\right]_0^{E_f}$$

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$$n_c = \frac{4\pi}{h^3}(2m)^{3/2} \times \frac{2}{3}\left[E_f^{3/2} - 0\right]$$

$$\boxed{n_c = \frac{8\pi}{3h^3}(2m)^{3/2} E_f^{3/2}}$$ — Learn.

* For fermi energy in terms of Conc^n of e^- at $t = 0K$:

$$E_f^{3/2} = \frac{3n_c}{8\pi} \frac{h^3}{(2m)^{3/2}}$$

Taking 2/3 root on both side

$$\boxed{E_f = \frac{h^2}{2m}\left(\frac{3n_c}{8\pi}\right)^{2/3}}$$

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Q. At low temp. copper has a free e^- concentration of $8.45 \times 10^{28}/m^3$ using the free e^- modal. Find the fermi energy of solid copper

$$\text{Conc}^n = 8.45 = n_c \qquad E_f = \frac{h^2}{8m}\left(\frac{3n}{8\pi}\right)^{2/3}$$

$$E_f = \frac{(6.63\times10^{-34})^2}{8\times 9.1\times10^{-31}} \times \left(\frac{3\times8.45\times10^{28}}{8\times 3.14}\right)^{2/3}$$

$$= 6.63$$

$$= \frac{4.39\times10^{-67}}{1.82\times10^{-30}} \times \left(\frac{6.42\times10^{58}}{25.12}\right)^{2/3}$$

1.12×10^{-18}

$$= 2.41\times10^{-37} \times \left(\frac{6.42\times10^{58}}{25.12}\right)^{2/3}$$

$\sigma = \frac{ne^2\tau}{m}$ | $J = \sigma E$ | $I = \tau X V$

$\sigma = \mu ne$ | $J = -nev_d$ | $E_F = \frac{1}{2}mv^2$

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Q. A conduction wire has a resistivity of 1.64×10^{-8} ohm at room temp. The fermi energy for such a conductor is 5.3 ev. There are 5.8×10^{28} es/m³

Calculate

1) relaxation time mobability.

$\rho = 1.64 \times 10^{-8}$

$n = 5.8 \times 10^{28}$

$R = \frac{\rho L}{A}$

$\frac{1}{\rho} = \frac{ne^2\tau}{m}$

$\frac{1}{\rho} = \frac{5.8 \times 10^{28} \times (1.6 \times 10^{-19})^2}{9.1 \times 10^{-31}} \times \tau$

$\frac{1}{1.64 \times 10^{-8}} = \frac{5.8 \times 10^{28} \times (1.6 \times 10^{-19})^2}{9.1 \times 10^{-31}} \times \tau$

$\tau = \frac{9.1 \times 10^{-31}}{1.64 \times 10^{-8} \times 5.8 \times 10^{28} \times (1.6 \times 10^{-19})^2}$

$\tau = 3.73 \times 10^{-14}$ s.

$\sigma = \mu E$

$\mu = \frac{\sigma}{ne} = \frac{1}{1.64 \times 10^{-8} \times 5.8 \times 10^{28} \times 1.6 \times 10^{-19}}$

$= 6.65 \times 10^{-3}$

$$\frac{1}{1.64 \times 10^{-8}} = \rightarrow \text{(6)} \times 5.8 \times 10^{28} \times 1.6 \times 10^{-19} \times v_d$$

$$v_d = \frac{1}{1.64 \times 10^{-8} \times 5.8 \times 10^{28} \times 1.6 \times 10^{-19}}$$

$$= \cancel{6.5} \times$$

$$= 0.056$$

Velocity of $e^{\ominus}$ = ?

$$\frac{25.12}{1.31 \times 10^{-66}}$$

$\sigma = \frac{ne^2\tau}{m}$ $K_B =$

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Fermi Energy $= \frac{1}{2}mv^2$

$$v^2 = \frac{2f(\epsilon)}{m}$$

$$V = \sqrt{\frac{2E_f}{m}}$$

$$V = \sqrt{\frac{2 \times 5.3 \times 1.6 \times 10^{-19}}{9.1 \times 10^{-31}}}$$

$$V = 13.63 \times 10^5$$

$V_f \times \tau =$ mean free path

$5.09 \times 10^{-8}\ m$

Q. Fermi level in silver is 5.5 eV at 0 K. Calculate the no. of free e^- per unit volume and Probability of occupation of e^-'s with 5.7 eV in silver at the same temp.

n_c and f_E

$$f(E) = \frac{1}{\quad}$$

$$n_c = \frac{8\pi}{3h^2}(2m)^{3/2}(E_f)^{3/2}$$

$$= \frac{8 \times 3.14}{3 \times (6.63 \times 10^{-34})^2}(2 \times 9.1 \times 10^{-31})^{3/2}(5.5 \times 1.6 \times 10^{-19})^{3/2}$$

$$= 2.957 \times 10^{-53}$$

$n_c = 5.87 \times 10^{28}\ /m^3$

Energy band gap

2.44 × 10^4

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than Semiconductors

$$F(E) = \frac{1}{1 + e^{\frac{(E - f_E)}{K_B t}}}$$

$$= \frac{1}{1 + e^{\frac{3.2 \times 10^{-20}}{0}}} = \frac{1}{1 + e^{-\infty}} = 0$$

Q Calculate fermi energy and fermi temp. in a metal. Given that fermi velocity of electron in the metal is 0.86×10^6 m/s

Soln:

$$E = \frac{1}{2} m v^2$$

$$= \frac{1}{2} \times 9.1 \times 10^{-31} \times (0.86 \times 10^6)^2 \text{ m/s}$$

$$= 3.363 \times 10^{-25} = 3.365 \times 10^{-19} \text{ J}$$

Fermi temp.: = 2.103 eV Ans

$$E_f = K_B T_F$$

$$T = \frac{E_f}{K_B}$$

$$= \frac{3.363 \times 10^{-25}}{1.36 \times 10^{-23}} = 2438 5.36$$

Ans

holes in valency band

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$N = 10^{23}/cc$ $K_B = 1.36 \times 10^{-23}$

$E_F = K_B T$

Q. At loco temp. Copper has a free $e^{\ominus}$ conc^{n} of 8.45×10^{-28} /m3 using the free e model find Fermi energy of solid copper.

~~n =~~

Conducter – 0

Semiconductor – < 3ev

Insulator – > 3ev.

→ Direct or Indirect Conductor!

* Band theory of a Solid:

- A solid is formed by bringing together isolated single atoms.
- Each atom when isolated has a discreate set of energy levels

1S, 2S, 2P, 3S, 3P

as all the N atoms approch one another to form a solid and In general

$N \approx 10^{23}/cc$

after quantum theory

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n=3 n=3
n=2 n=2
n=1 n=1

Atom 1 Atom 2.

When the distance b/w two atoms is less then interatomic distance. then the Energy levels of atoms are splated into n distint levels.

So, this is form a almost continious band.

The crystal of Energy level very close to one another is known as Energy band.

- Amount of spelting is different for different energy levels, Lower Energy level. are ~~stated~~ ~~Less~~ splited less then the higher Energy level.

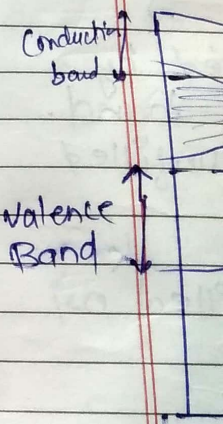
It is due to as the lower energy levels are not influence ~~are~~ by the presence of nearby atom, where as higher Energy level intract strongly with the nearby atom

- Each elec level

whe and

- This

Con



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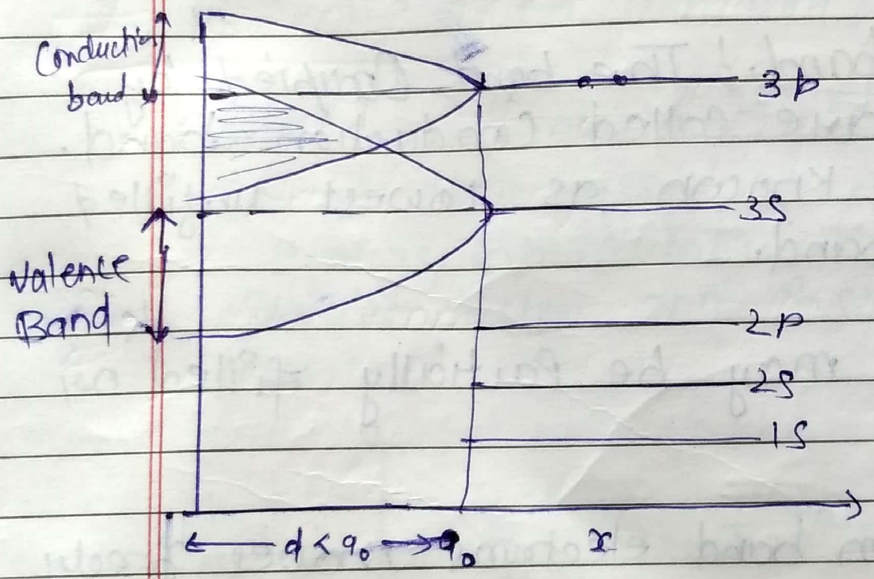
- Each band has a total ~~of~~ N individual ~~electrons~~ Energy levels. and each level contain the ~~two~~ 2(2l+1)

$$2(2l+1)N \text{ electrons}$$

↳ 2 is due to spin quantum no. (s) = ±½

where N is the no. of Energy levels. and l → orbital Quantum no.

- This band theory ~~needs~~ leads to the classification of theory into Conductor, insulator and semiconductor.



- e⁻'s in the Outermost shell are called Valance electrons and the Band. form by a series of Energy levels containing the valance e⁻ are known as valance band theory

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* Valance band :
The band which is occupied by the valance electron or band ~~occupie~~ having the heighest band energy are known as valence band.

Properties:
- Valance band may be partially or fully ~~field~~ filled debends on the nature of Crystall.
- Valance band Never be empty.

* Conduction band.: The band Occupied by free e⊖ are called Conduction band. It is also known as Lowest unfilled energy band.
- This band may be Partially filled or empty.
- In Conduction band electrons moves freely
- If has empty Conduction band it means there is no conduction current

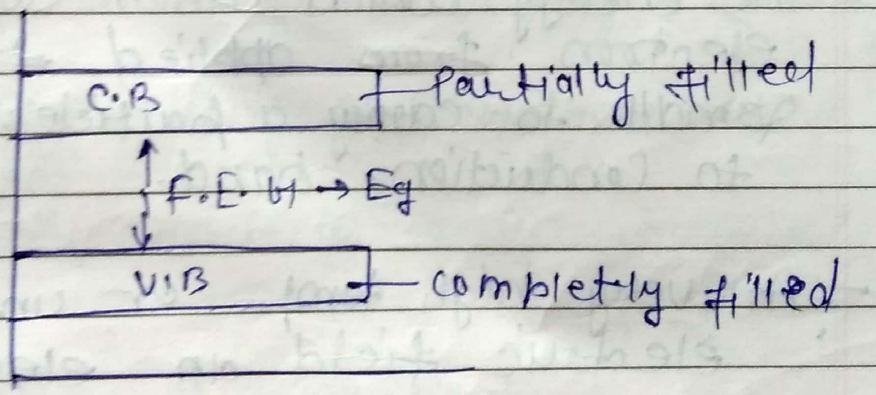
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* Forbidden Energy gap:
The seperation b/w C/B and V/B is known as forbidden Energy gap.

- There is no allowed energy state in this gap it means there is no $e^{\ominus}$ normally exist in this gap.

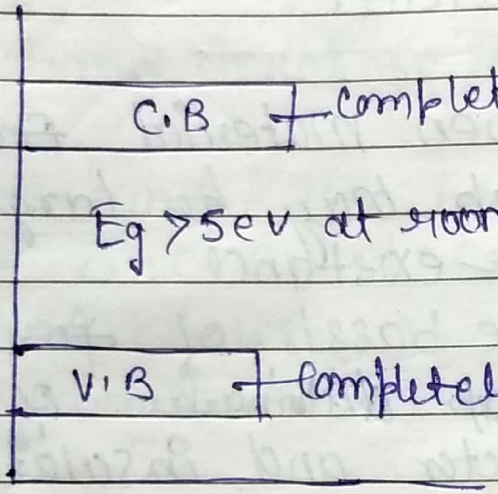
- Greater the forbidden Energy Gap more tightly the valence $e^{\ominus}$ are bound to be nucleus.

- For any given material forbiddan energy gap may be large or small or non-existance
So, on the basis of forbiddan energy gap distinction of Conduction Semiconducter and insulater can be described



* Insulators :- In insulators Valence e's are tightly bound with the Parent atom

- Practically no electron in the conduction band and valence band is completely filled
- Valence and Conduction band are near about greater then 5ev apart



- The energy which can be supplied to an electron from applied field is to small to carry a particle from valence to Conduction band.
- At very high temp. or under high electric field an electron can jump to conduction band this is by Some material which is insulator at room temp become Conductor at high temp. this is called breakdown of insulating material

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Semiconductor:

- For Semiconductor near about absolute Zero temp. the valency band is completely filled and no $e^{\ominus}$ in Conduction band so no Current flow in semiconductor at 0K temp. and it behave as an Insulater.

- If provided energy

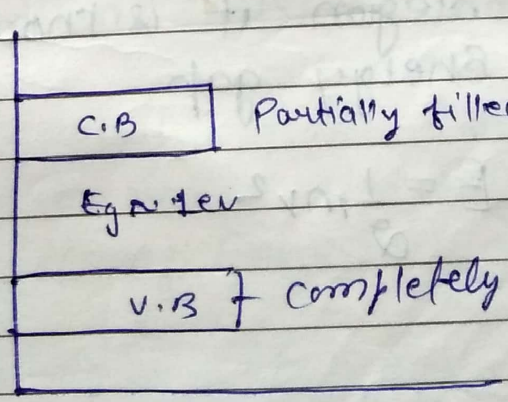
$$E \geq E_g \approx 1 \text{ ev.}$$

then $e^{\ominus}$ can be Lifted to Conduction band by imparting some energy.

- The energy imparted by the heat at room temp is sufficient to lift $e^{\ominus}$ from valency Band to C.B and at room temp. semiconducter are capable of Conducting current.

- The Conductivity of semiconductor is nearly

$$\sigma \approx 10^{2} - 2^{-1} \text{ cm}$$

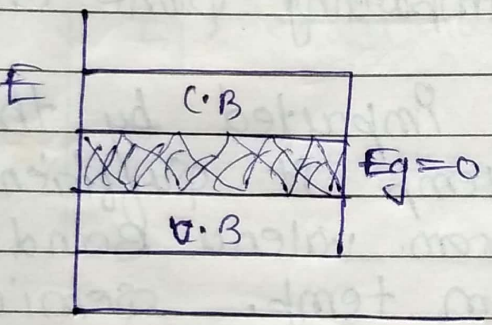


Diagram

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* Conductor :- There is no forbiddan gap b/w V.B and C.B

- V.B and C.B are overlapped
- $e^{\ominus}$ in ~~conductor~~ C.B moves randomly throw out the solid that is the region that $e^{\ominus}$ are known as free electrons.
- Due to overlapping of V.B and C.B is slightly pott. difference across Conductors causes free electron to constituent current



Energy

* Forbidden ~~band~~ gap :
The energy b/w C.B and V.B are known as forbidden gap and there is no Energy Level b/w V.B and C.B due to this region it is know as Forbidden energy gap

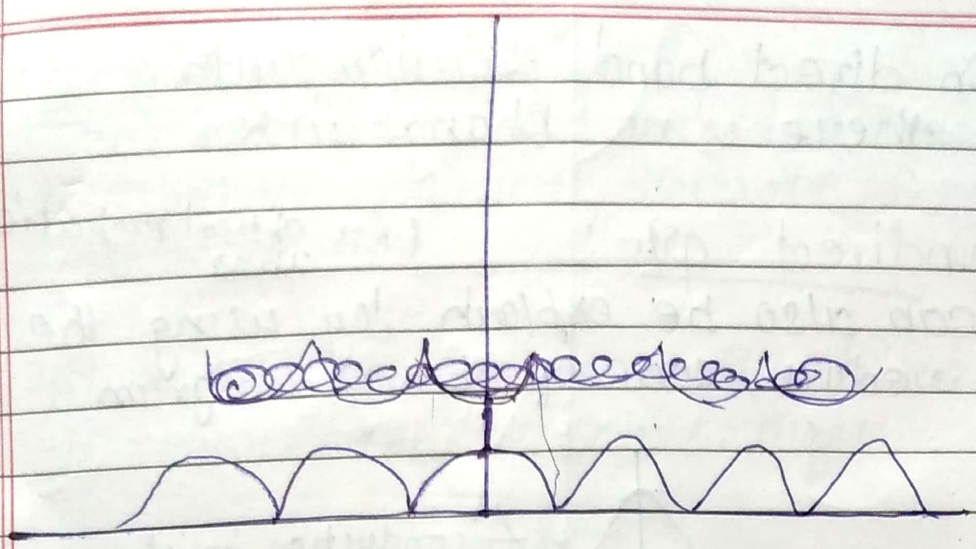
$$E = \frac{1}{2} m v^2$$

$P = \hbar K$

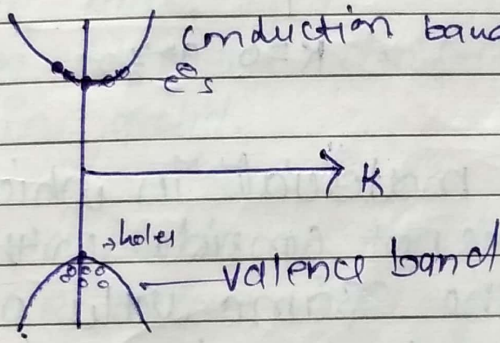
$\lambda = \frac{h}{p}$

$K = \frac{2\pi}{\lambda}$

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* Direct energy band gap: (Laser diode use) The Direct ~~an~~ Semiconductor can be explain by reduced zone of E-K diagram.



The material in which in E-K diagram the minima of conduction band coincide with the maxima of valence band at the same value of K. then it is known as direct band gap S/C

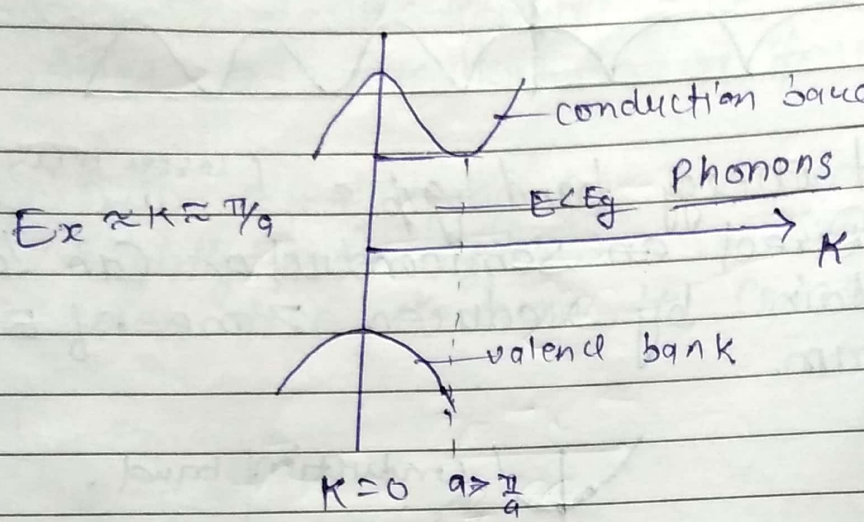
- $e^{\ominus}$ can jump from conduction to valence band directly by emitting a photon of Eenergy = E_g

$$E = E_g$$

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- In direct band semiconductor there is no change in K

* Indirect s/c : (for optical properties)
can also be explain by using the reduce zone of E-K diagram.



The material in which minima of CB does not coincide with maxima of VB at the same value of K is known as indirect semiconductors.

- Indirect s.c $e^{\ominus}$ does not jump directly from C.B to V.B due to this it suffer a change in energy and momentum.

- In indirect s.c change in K as well energy which is given to the lattice in form of heat.

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* Effective mass :- (m^*)

The Experintely determined $e^\ominus$ mass is slightly different then the free mass in solid.

this experimently determine $e^\ominus$ mass is known as effective mass

$$m^* = \frac{\hbar^2}{\left(\frac{d^2E}{dk^2}\right)}$$

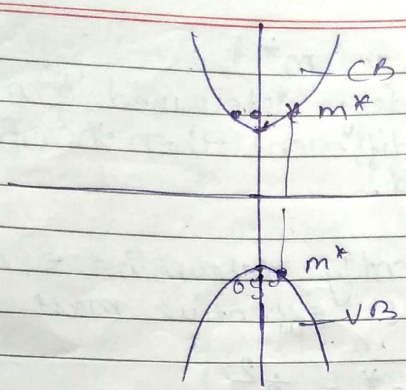
- The difference in Eff. mass of $e^\ominus$ to the free mass of $e^\ominus$ is due to the interaction b/w the drifting $e^\ominus$'s and atoms in solid.

- Eff. mass depends on the Location of $e^\ominus$ in the allow Energy band

- for the crystall in which energy band is nearly full the negative charge and negative mass vacancy may be consider as positive charge and positive negative mass particle is known as holes

- The value of $\frac{d^2E}{dk^2}$ → Curvature of Energy Level.

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for one particular K value
Shows two m*

As $E = \frac{p^2}{2m}$

$E = \frac{\hbar^2 k^2}{2m}$

$\frac{dE}{dk} = \frac{\hbar^2 k}{m}$

$\frac{d^2E}{dk^2} = \frac{\hbar^2}{m}$

$m^* = \frac{\hbar^2}{\frac{d^2E}{dk^2}}$

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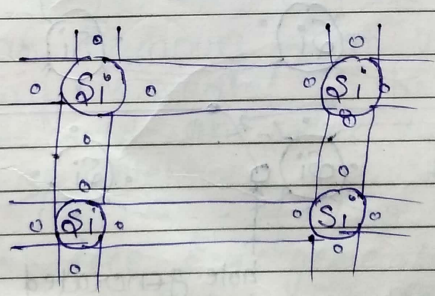
* Semiconductors:

Intrinsic	Extrinsic
→ σ is dependent on temp.	→ They are impure S/c
→ It is generally not used for device formation	→ σ can be increase by doping some elements.
→ they are pure Semiconductor	→ σ may be independ on temp. they are widely used in formation of devices.
→ they have very low Conductivity.	

Intrinsic:

* temp. dependent of S/c:

(1) at T = 0K



- At T = 0 all the $e^{\ominus}$s are tightly bound with semiconductor atom where as valence electron are engeinged in covelent bonding

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and at t=0 covalent bonding is very Strong and there is no free electron in Conduction band and Semiconductor behave as an Insulator.

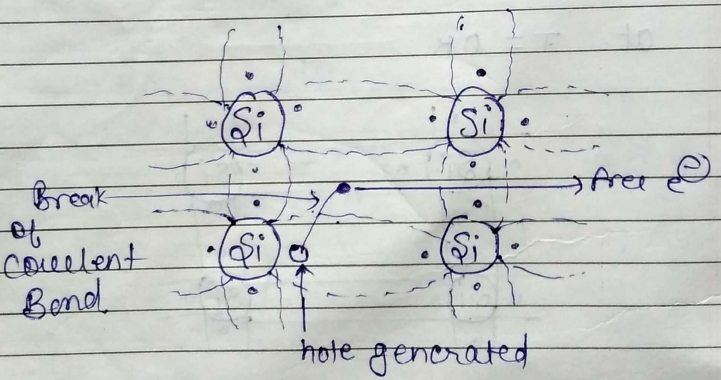
C.B empty

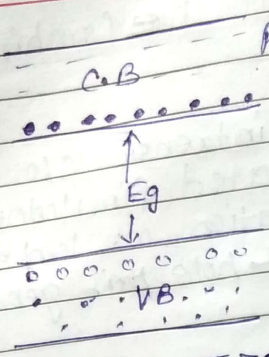
Eg ≈ 1.1eV

V.B completly filled & bound by covelent bonding.

T = 0K

(2) at T > 0 K





T > 0

- At T > 0K Some covelent Bond Break due to thermal Energy and valence $e^{\ominus}$ become free higher the temp. more bonds are broken and $e^{\ominus}$s are free to move randomely in the void space b/w the atoms in the crystal.

- When an $e^{\ominus}$ moves from V.B to C.B a vacency is created in broken covelent bond and this vacency is known as holes.

- when a free $e^{\ominus}$ is generated simultaneously a hole is created so, $e^{\ominus}$ and holes always generation in pair.

- Generation and recombination

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* Generation and Recombination:

* Generation :

In intrensic s/c $e^{\ominus}$'s and hole pair are generated similatonusly due to thermal agitation or temperature. this is called e^{-}-hole pair generation

Covane

Covalent bond + thermal energy $\xrightarrow{\text{rupture}}$ $e^{\ominus}$ + holes

At any temperature the no. of $e^{\ominus}$ generated is equal to no. of hole produce or Conc^{n} of $e^{\ominus}$ in C.B is equal to Conc^{n} of holes in V.B

- Recombination :

$e^{\ominus}$ in Conduction band Loss its energy due to collision with other particle in the lattice and falls into the valence Band. then free $e^{\ominus}$ falls into V.B it mess mers with hole this process is called recombination

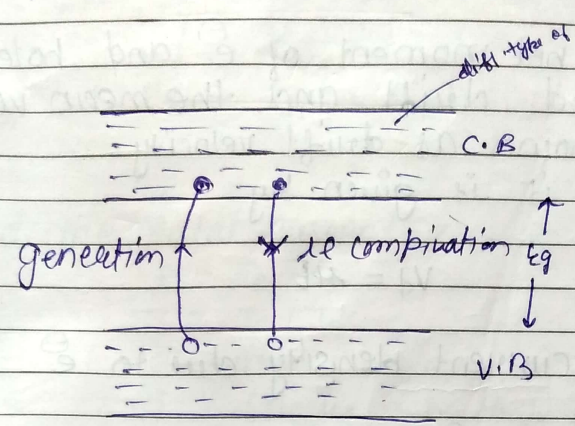
$e^{\ominus}$ + hole $\longrightarrow$ Covalent + Energy

free $e^{\ominus}$ transferm into valence $e^{\ominus}$ and rupture covalent bond re-bugs in this process $e^{\ominus}$-hole pair disappes and energy is release.

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and released Energy in form of thermal Energy.

At the given temp. Rate of generation is equal to rate of recombination



* Intrinsic Conductivity:

At any temp. no. of $e^{\ominus}$ generated per unit volume is equal to no. of holes generated per unit volume

$n = p = n_i$ → intrinsic density
or
intrinsic Conc^{n}.

at a temp T avg. K.E

$$\frac{1}{2} m v_{th}^2 = \frac{3}{2} KT$$

In Presence of electric field in Steady State condition moment of $\ominus e$ opposite to the electric field and moments of holes among the dirn of Electric field.

The net moment of $\ominus e$ and holes is called drift and the mean velocity is known as drift velocity. and it is given by

$$v_d = \mu E$$

the current density due to $\ominus e$

$$J_e = n e v_d$$

and due to hole

$$J_h = p e v_d$$

the Conductivity

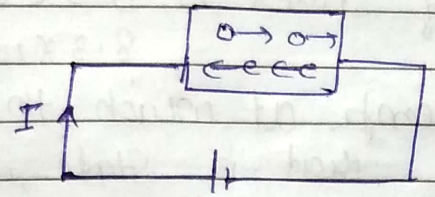
$E = \frac{v_d}{\mu}$

$v_d = \mu E$

$$\sigma = \frac{J}{E} = \frac{n e v_d \mu}{v_d}$$

$$\sigma_e = n e \mu_e$$

$$\sigma_h = p e \mu_h$$



and the total current

$$I = I_e + I_h$$

$$J = J_e + J_h$$

$$= n e v_d + p e v_d$$

$$J = (n e \mu_e + p e \mu_h)$$

$$J = n_i e E (\mu_e + \mu_h)$$

and $$\boxed{\sigma = n_i e (\mu_e + \mu_h)}$$

- As variation of mobality with temp. is very small. so, the variation of Conductivity is directly proportional to $n_i e(T)$

$$\sigma(T) \propto n_i e(T)$$

$$\sigma(T) \propto n_i(T).$$

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At what temp we can expect a 10%. probability that e in a silver have an energy which is 1% above the Fermi energy.

the E_f of Silver is 5.5 eV

8.8×10^{-19} J.

Find the temp. at which there is 1% probability that a state with energy 2 eV is occupied given that

$E_f = 1.5$ eV

$= 2.4 \times 10^{-19}$ J

(1) $$f(E) = \frac{1}{1 + e^{E - E_F / K_B T}}$$

$$\frac{1}{100} = \frac{1}{1 + e^{E - 2.4 \times 10^{-19}}}$$

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$$T = \frac{4.605}{2 \times 1.38 \times 10^{-23}} \Big/ \left(3.2 \times 10^{-19} - 3.84 \times 10^{-19}\right)$$

$$= \frac{6.26 \times 10^{-23}}{-6.4 \times 10^{-20}}$$

$$= 9.78 \times 10^{-4}$$

$$F(E) = \frac{1}{1 + e^{E - E_F / K_B T}}$$

$$\frac{1}{100} = \frac{1}{1 + e^{\frac{3.2 \times 10^{-19} - 2.4 \times 10^{-19}}{1.38 \times 10^{-23} T}}}$$

$$1 + e^{\frac{8 \times 10^{-20}}{1.38 \times 10^{-23} T}} = 100$$

$$e^{\frac{8 \times 10^{-20}}{1.38 \times 10^{-23}}} = 100 - 1$$

$$e^{\frac{8 \times 10^{-20}}{T \times 1.38 \times 10^{-23}}} = 99$$

$$\frac{8 \times 10^{-20}}{T \times 1.38 \times 10^{-23}} = \ln 99$$

$$T = \frac{8 \times 10^{-20}}{4.59 \times 1.38 \times 10^{-23}}$$

$$= \frac{8 \times 10^{-20}}{6.33 \times 10^{-23}} = 1263.8$$

Ans

$\log e = \ln$.

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Sol^{n}:-

8.8×10^{-21}

$$\frac{10}{100} = \frac{1}{1 + e^{\frac{E - E_f}{KT}}}$$

$E_f = 5.5\ eV = 8.80 \times 10^{-19}$

~~$E = 8.8 \times 10^{-19} = 8.8 \times 10^{-21}$~~

$$1 + e^{\frac{-8.712 \times 10^{-19}}{1.38 \times 10^{-23}}} = 10$$

$$e^{\frac{-8.712 \times 10^{-19}}{1.38 \times 10^{-23} \times T}} = 9$$

$$T \times -8.719 \times 10^{-19} = 2.19$$

$$T = \frac{2.19}{8.7 \times 10^{-19}} = 2.517 \times 10^{18}\ k$$

$$e^{\frac{-8.712 \times 10^{-19}}{1.38 \times 10^{-23} \times T}} = 9$$

$$\frac{-8.712 \times 10^{-19}}{1.38 \times 10^{-23} \times T} = 2.19$$

$$T = \frac{-8.712 \times 10^{-19}}{2.19 \times 1.38 \times 10^{-23}}$$

$$= \underline{8.719 \times 10^{-19}}$$

8.8×10^{-21}

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E=

$$\frac{10}{100} = \frac{1}{1 + e^{E - E_F / K_B T}}$$

$$\frac{1}{10} = \frac{1}{1 + e^{\frac{8.88 \times 10^{-19} - 8.80 \times 10^{-19}}{1.38 \times 10^{-23} \times T}}}$$

$$1 + e^{\frac{0.08 \times 10^{-19}}{1.38 \times 10^{-23} \times T}} = 10$$

$$= 2.19$$

$$\frac{579.71}{T}$$

$$T = \frac{579.7}{2.19} = 264.7.$$

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Intrinsic S.C

Carrier Concentration & density of charge Carriers :

As in semiconductor $e^{\ominus}$ and holes are charge particle so, they together are called charge carriers

Carrier Concentration is equal to no. of $e^{\ominus}$ in C.B per unit volume

Carrier conc^n = no. of $e^{\ominus}$ in CB/vol. $\rightarrow n$
= no. of holes in V.B/vol. $\rightarrow p$

$e^{\ominus}$ density of $e^{\ominus}$ conc^n in conduction c.band

No. of electrons whose energy lies b/w energy interval E and E+dE in conduction band is given by

$$dn = N(E) f(E) dE$$

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Now $N(E) = \frac{4\pi}{h^3}(2m_e^*)^{3/2} E^{1/2} dE$ — (A)

In conduction band for energy $E > E_c$

$$N(E) = \frac{4\pi}{h^3}(2m_e^*)^{3/2}(E-E_c)^{1/2} dE \quad -(a)$$

$$F(E) = \frac{1}{1+e^{(E-E_f)/KT}} \quad -(B)$$

For $E > E_c$ in conduction band

$$E - E_F >> KT$$

then eq^n (B) is as

$$F(E) = e^{-[E-E_f]/KT}$$

Now Substitute the value of $F(E)$ and $N(E)dE$ in eq^n (A)

then

$$n = \int_{E_c}^{\infty} \frac{4\pi}{h^3}(2m_e^*)^{3/2}(E-E_c)^{1/2} \cdot e^{-(E-E_f)/KT} dE$$

$$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2} \int_{E_c}^{\infty} (E-E_c)^{1/2} e^{-(E-E_f)/KT} dE$$

$$\int_0^\infty x^{1/2} e^{-x}\, dx = \frac{\sqrt{\pi}}{2}$$

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$$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2} e^{-\frac{[E_c - E_F]}{KBT}} \int_{E_c}^{\infty} (E-E_c)^{1/2} \cdot e^{-(E-E_c)/K_T}\, dE$$

Now $\frac{E - E_c}{KT} = x$

when $E \to E_c$
$x = 0$

$\frac{dE}{KT} = dx$

$$n = \frac{4\pi}{h^3}(2m_e^*)^{3/2} e^{-(E_c - E_F)/KT} \int_0^\infty x^{1/2}(KT)^{1/2} \cdot e^{-x}(KT)\, dx$$

$$= \frac{4\pi}{h^3}(2m_e^*)^{3/2} e^{-(E_c - E_F)/KT} (KT)^{3/2} \int_0^\infty x^{1/2} e^{-x} dx$$

$$n = \frac{4\pi}{h^3}(2m_e^* KT)^{3/2} e^{-\frac{(E_c - E_F)}{KT}} \cdot \frac{\sqrt{\pi}}{2}$$

(2) Conc^n

if c
b/w
valenc

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en

and

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$$n = 2\left[\frac{2 m_e^* KT}{h^2}\right]^{3/2} e^{-\frac{(E_c - E_F)}{KT}}$$

$$n = N_c\, e^{-(E_c - E_F)/KT} \quad \text{— (1)}$$

$N_c \Rightarrow$ effictive density of state in C.B

N_c is a constant

$$N_c = 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2}$$

(2) Conc^n of holes in valence band:-

if $dp \Rightarrow$ no. of holes whose energy lies b/w energy interval E and E+dE in valence band the dp =

$$dp = N(E)[1 - f(E)]\,dE \quad \text{— (1)}$$

where $N(E)dE \Rightarrow$ density of states in the energy interval E and E+dE

and $[1 - f(E)]$ is state of Energy which is vacant.

$$\int_0^\infty x^{1/2} e^{-x}\,dx = \frac{\sqrt{\pi}}{2}$$

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It means it is not occupied by an electron.

$$[1 - f(E)] = 1 - \frac{1}{1+e^{(E-E_F)/KT}}$$

$$= 1 - \left[1 + e^{(E-E_F)/KT}\right]^{-1} \qquad E - E_F \gg KT$$

$$= 1 - \left[1 - e^{(E-E_F)/KT} + \cdots\right]$$

$$1 - f(E) = e^{-(E-E_F)/KT}$$

Now substitute the value in eq^n (1)

then

$$\int dp = \int_{-\infty}^{E_V} \frac{4\pi}{h^3}(2m_h^*)^{3/2}(E_V - E)^{1/2} e^{(E-E_F)/KT}\,dE$$

(no. of holes in VB)

$$p = \frac{4\pi}{h^3}(2m_h^*)^{3/2} e^{-(E_F-E_V)/KT} \int_{-\infty}^{E_V} (E_V - E)^{1/2} e^{-(E_V-E)}\,dE$$

Let $\frac{E_V - E}{KT} = x$

$$\frac{dE}{KT} = -dx$$

$$dE = -KT\,dx$$

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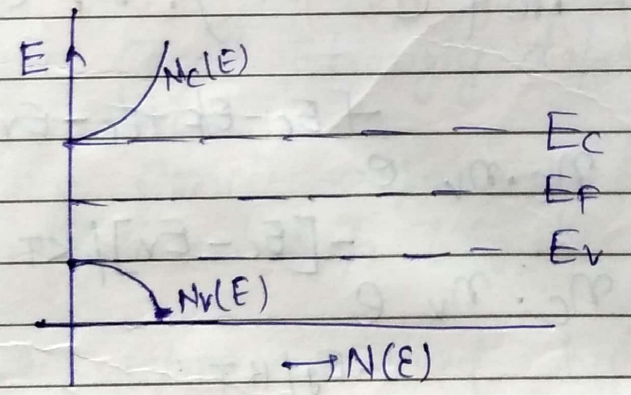
$$= \frac{4\pi}{h^3}(2m_h^*)^{3/2} e^{-\frac{(E_F - E_V)}{KT}} \int_0^\infty x^{1/2} (KT)^{3/2} e^{-x} dx$$

$$= \frac{4\pi}{h^3}(2m_h^*)^{3/2} (KT)^{3/2} e^{-\frac{(E_F - E_V)}{KT}} \frac{\sqrt{\pi}}{2}$$

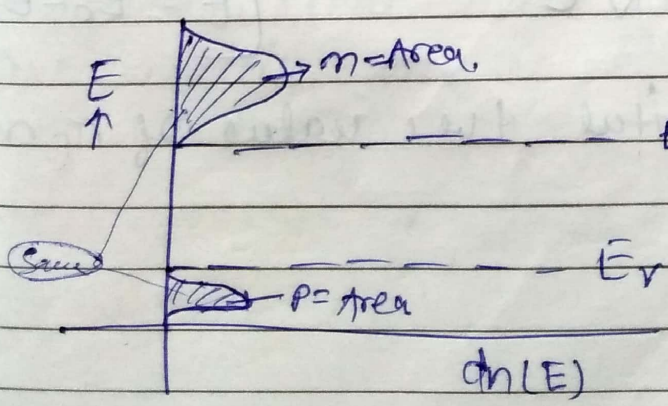
$$p = 2\left[\frac{2\pi m_h^* KT}{h^2}\right]^{3/2} e^{-[E_F - E_V]/KT}$$

$$\boxed{p = N_V e^{-[E_F - E_V]/KT}} \quad (1)$$

Here N_V is the effective density of state in valence band



$N(E)$ = density of states



n = no. of $e^\ominus$/vol. in C.B

P = no. of holes/vol in V.B.

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* Intrinsic Conc^n of Charge Carriers :

Intrinsic ~~carrier~~ carriers Conc^n :

At any temp. T, no. of electrons

no. of electron generated = no. of holes generated

$$n = p = n_i$$

where n_i is calculated the intrinsic density or intrinsic conc^n.

$$n_i^2 = n \cdot p \quad \text{---(1)}$$

Now, substitute the value of n and p in eq^n

$$n_i^2 = N_c \left(e^{-\frac{(E_c - E_f)}{KT}} \right) \cdot n_v \, e^{-(E_f - E_v)/KT}$$

$$= n_c \cdot n_v \, e^{-[E_c - E_f + E_f - E_v]/KT}$$

$$= n_c \cdot n_v \, e^{-[E_c - E_v]/KT}$$

$$n_i^2 = n_c \cdot n_v \, e^{-E_g/KT} \qquad [E = E_c - E_v]$$

Now substitute the value of n_c and n_v

$$n_i^\circ = 2\left(\frac{2\pi KT}{h^2}\right)^{3/2} (m_e^* m_h^*)^{3/4} e^{-\frac{Eg}{KT}}$$

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$$n_i^{\circ 2} = 4\left(\frac{2\pi m_e^* KT}{h^2}\right)\left(\frac{2\pi m_h^* KT}{h^2}\right) e^{-Eg/KT}$$

$$n_i^\circ = \sqrt{2\left(\frac{2\pi m_e^* m_h^* KT}{h^2}\right)^{3/2} e^{-Eg/KT}}$$

$$n_i^\circ = 2\left(\frac{2\pi KT}{h^2}\right)^{3/2} (m_e^* m_h^*)^{3/4} e^{-Eg/2KT}$$

this eq^n gives the intrinsic carrier Conc^n. at temp. T

$$n_i^\circ = 2\left(\frac{2\pi m_e^* m_h^* K}{h^2}\right)^{3/2} T^{3/2} e^{-Eg/2KT}$$

then it shows that the carrier Conc^n in intrinsic S/C varies with temp.

- Intrinsic conc^n is independent of fermi level
- Intrinsic conc^n strongly depends on the temperature
- Intrinsic conc^n expomently depends on Energy band gap (Eg)

And 2 represent that by broken of one covalent bond to charge carriers are produce one is $e^\ominus$ and another is hole.

Variation Presence of fermi level in intrinsic semiconductor:

As in intrinsic s/c $e^{\ominus}$ and holes are generated in pair then

$$n = p = n_i$$

$$n_c e^{-[E_c - E_f]/KT} = N_v e^{-[E_f - E_v]/KT}$$

$$2\left(\frac{2\pi m_e^* KT}{h^2}\right) e^{-[E_c - E_f]/KT} = 2\left[\frac{2\pi m_h^* KT}{h^2}\right] e^{-[E_f - E_v]/KT}$$

Dulo'

$$m_e^{*3/2} e^{-[E_c - E_f]/KT} = m_e^{*3/2} e^{-[E_f - E_v]/KT}$$

$$e^{-[2E_f - E_c - E_v]/KT} = \left(\frac{m_h^*}{m_e^*}\right)^{3/2}$$

taking ln of both side.

$$\frac{-2E_f + E_c + E_v}{KT} = \frac{3}{2} \ln\left(\frac{m_h^*}{m_e^*}\right)$$

If we assume that Effective mass of $e^{\ominus}$.

$$m_e^* = m_h^*$$

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then,

$$E_f = \frac{E_c + E_v}{2}$$

As $E_c - E_v = E_g$

$$E_f = \frac{E_c - E_v}{2} + E_v$$

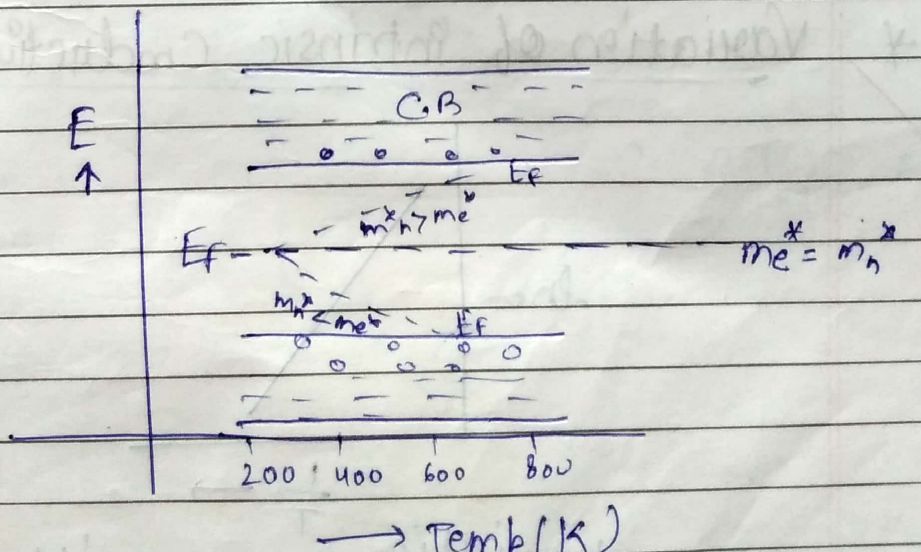
If we assume that top of V.B (i.e E_v) as a zero Energy level so, we can take $E_v = 0$

then.

$$\boxed{E_F = \frac{E_g}{2}}$$

Imp:- Fermi level is not an allowed energy level in Semiconductor. It only serves as an reference energy with reference to which we specify the energy of $e^\ominus$ and holes in S/C.

* Variation of fermi level with temp. in intrinsic S/C:



Variation of E_F with temp. in intrinsic S.C

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(i) if $m_h^* = m_e^*$ then.

E_f lies exactly b/w the E_c & E_v.

(ii) if $m_h^* > m_e^*$ then

E_f slightly towards the C.B

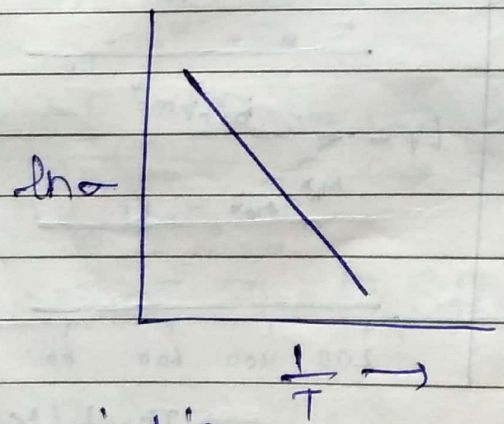
(iii) if $m_h^* < m_e^*$ then

E_f shift towards the V.B

(iv) In most of the material the shift of fermi level on account of when $m_e^* \neq m_h^*$ is insignificant

(v) Fermi level in an intrinsic S/C may be consider as independent of temp. so, we can say that E_f lies middle of the energy gap.

* Variation of intrinsic conductivity with temp.



Variation of σ with temp.

→ Extrinsic semiconductor

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As $\sigma = n_i e [\mu_e + \mu_h]$

$$n_i e = (n_c n_v)^{1/2} e^{-E_g/2KT}$$

$$\sigma = (n_c n_v)^{1/2} e^{-E_g/2KT} (\mu_e + \mu_h).$$

$$\sigma = \sigma_0 e^{-E_g/2KT}$$

$$\sigma_0 = n_c n_v^{1/2} (\mu_e + \mu_h)$$
$$= \text{Constant}$$

$$\ln\sigma = \ln\sigma_0 - \frac{E_g}{2KT}$$

Conductivity increases with temp.

* Extrinsic Semiconductor:
Depends on the types of impurity added in pure semiconductor. Extrinsic Semiconductor are divided into two type

Extrinsic

↓

n-type

P-type Ex. SC

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→ n type :
It is found by adding pentavalent impurity. and these impurities are known as dopant
Ex: Phosphorous,
Arsenic
Antimony

→ P type : They are found by adding trivalent impurity and dopant are
Boron
Indium
Gallium

* n type Extrinsic Semiconductors :
- When a small amount of Pentavalent impurity is doped in pure semiconductor it is known as n-type S/c.

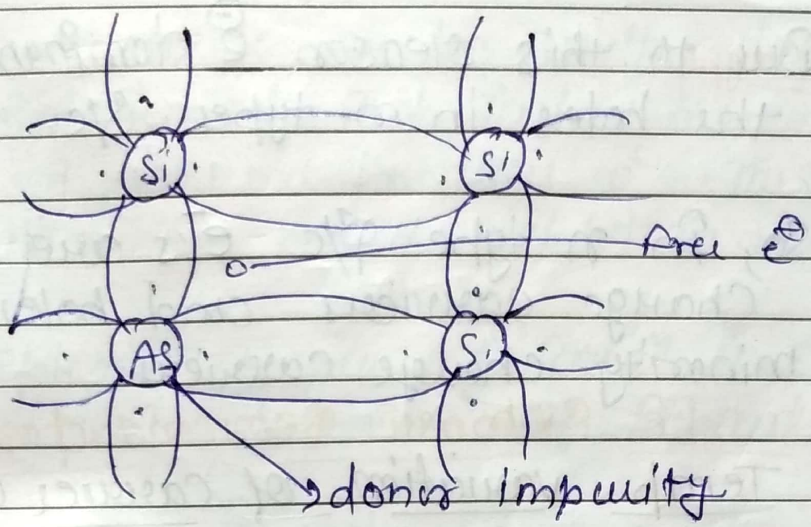
- Such type of impurity which produce n-type S/c are known as donor impurities. because they are donate or provide free electrons to the S/c crystal.

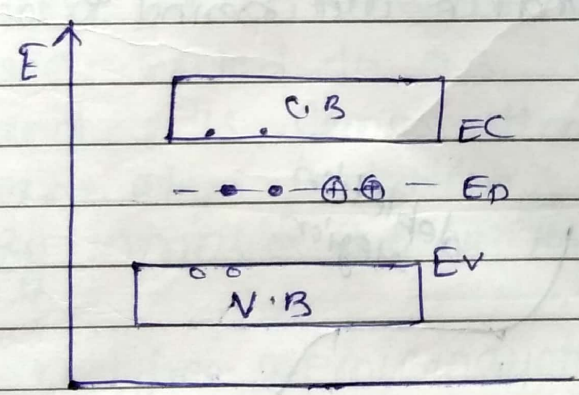
- For Ex: Arsenic has five valence $e^{\ominus}$'s and when it add in germanium crystal then four valence $e^{\ominus}$ of Arsenic formed covalent bond with the near about Germanium atom and valence $e^{\ominus}$ of Arsenic is free

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The amount of energy needed to the test this free $e^{\ominus}$ from Arsenic is very small which is near about 0.01 eV for Ge.

These free $e^{\ominus}$ work as a carrier charger in this system.





E bandding of n types.

E_D ⇒ Energy levels of Donor Atom

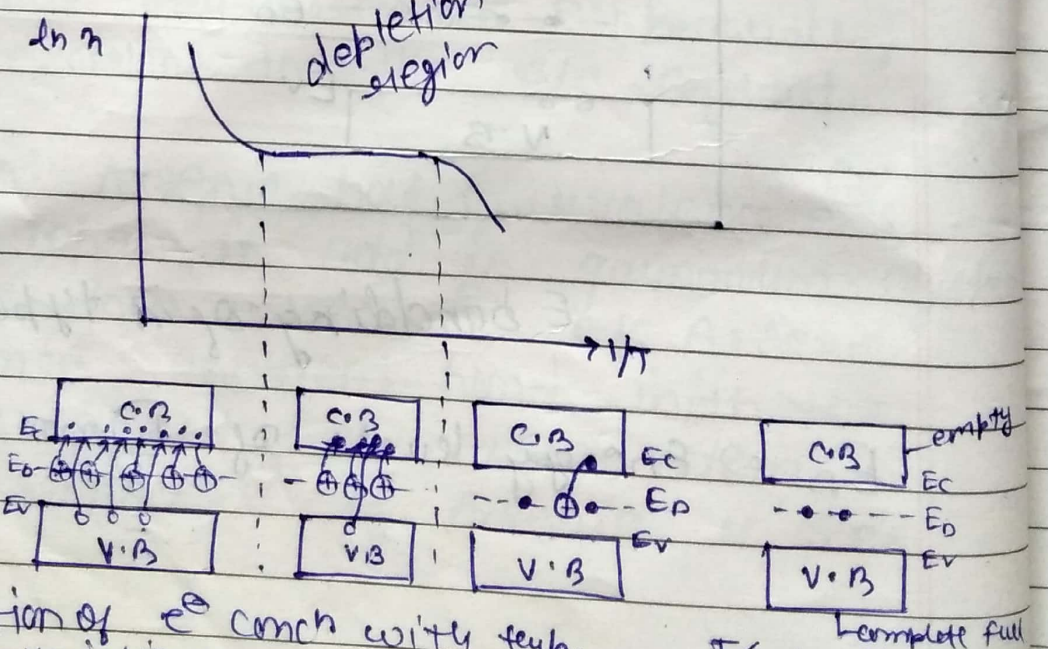
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- By addition of pentavalent impurity many new free e^- are produced.
- Thermal energy of room temp. still generate a few e^--hole pair. However he no. of free e^- provided by pentavalent impurity far exceeds no. of holes
- Due to this reason e^- dominate over the holes in n-type S/c.

So, In n-type S/c e^- is are majority charge carriers and holes are minority charge carriers.

* Temp. variation of carrier Conc^n. in n-type S/c :

At 0K Donar atoms are not ionised it means Donar e^- are bound to ther donar atom



Variation of e^- Conc^n with temp. or variation of

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So, Covalent bond is empty and V.B is Conduction Complete filled so, as behave as insulator

- Slightly elimated temp. Donar atoms are ionsised at donar $e^{\ominus}$'s are go into the Conduction band by getting Energy from Lattice vibration and in this process holes are not produces in V.B

→ At T= 100 K all the donar atoms ionised and further increase the temp. it does not produces $e^{\ominus}$. This region is called depletion region

- In depletion region $e^{\ominus}$ conc^{n} in C.B is equal to Conc^{n} of Dopant atoms

$$n_n \approx N_D$$

- When T > 100 K Some of $e^{\ominus}$'s from V.B are exited to C.B So, In Conduction band $e^{\ominus}$'s Comes through either
  i) Donar atom ionisation
  ii) By intrinsic Process produce holes in V.B

- In n-type semiconductor Carriers are independent of temp. in depletion region and curren in n-type s/c due to negative charge carriers.

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* Carrier Conc^n in n-type s/c at Low temp :-
The conc^n of donor in the material = N_D

at zero K (0K) E_D is near to C.B (E_C) and donor atom are not ionised

at T > 0K E_D is near to E_C & donor atom are ionised

by increasing the temp. the conc^n of $e^\ominus$ in C.B increased

$$n = N_D^+$$

$$n = N_D - N_D^\circ$$

where $N_D^+ \Rightarrow$ no. of donor atom ionised.
$n = N_D \Rightarrow N_D^\circ \rightarrow$ " " " " are left unionized

$$N_D^+ = N_D - N_D^\circ$$
$$= N_D \left[1 - f(E_D)\right]$$

As Fermi Level (E_F) in n-type s/c lies in few K_BT above then

$$n = N_D^+ = \frac{N_D}{1 + e^{+[E_F - E_D]/KT}} \quad \text{— (1)}$$

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Now, Conc^n of $e^{\ominus}$ in C.B

$$n = N_c e^{-(E_c - E_F)/KT} \quad \text{---(2)}$$

Now eq^n (1) and (2)

$$\frac{N_D}{1 + e^{(E_F - E_D)/KT}} = N_c e^{-[E_c - E_F]/KT}$$

Now taking log both side.

$$\frac{E_D - E_F}{KT} + \frac{E_c - E_F}{KT} = \ln \frac{N_c}{N_D}$$

$$E_D - E_c - 2E_F = KT \ln \frac{N_c}{N_D}$$

$$E_F = \frac{E_D + E_c}{2} - \frac{KT}{2} \ln \frac{N_c}{N_D}$$

$$= \frac{E_D + E_c}{2} + KT \ln \frac{N_D}{2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2}}$$

at $T = 0K$

$$E_F = \frac{E_D + E_c}{2}$$

$$\exp\left[\frac{E_F - E_c}{KT}\right] = \exp\left[\left(\frac{E_D + E_c}{2}\right) + KT \ln \frac{N_D}{2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2}} - \frac{E_c}{KT}\right]$$

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$$= \exp\left[\frac{E_D - E_C}{2KT} + \frac{1}{2}\ln\frac{N_D}{2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2}}\right]$$

$$= \exp\left[\frac{E_D - E_F}{2KT}\right] \cdot \left[\frac{N_D}{N_2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2}}\right]$$

AS

$$n = n_c \exp\left[\frac{E_F - E_C}{KT}\right]$$ So

So, $$n = n_c \exp\left[\frac{E_D - E_C}{2KT}\right] \cdot \left[\frac{N_D}{2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2}}\right]^{1/2}$$

$$n = 2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2} \exp\left[\frac{E_D - E_C}{2KT}\right]\left[\frac{N_D}{2\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/2}}\right]^{1/2}$$

Q1

$$n = (2N_D)^{1/2}\left(\frac{2\pi m_e^* KT}{h^2}\right)^{3/4} e^{\frac{E_D - E_C}{2KT}}$$

* P-ty
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* P-type Extrinsic S/c:

- When a trivalent impurity is added to a pure s/c it is called P type s/c.

- Such impurities which ~~prod~~ produce P-type s/c are called acceptor impurities because hole ~~created~~ created can accept

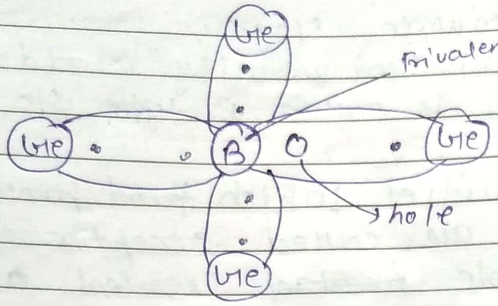
- The Examples are Gralium, Indium and Boron

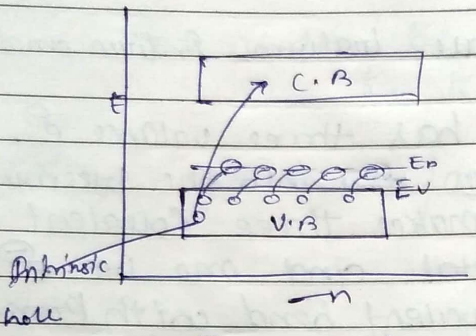
- For Ex. Boron has three valance $e^{\ominus}$. So each atom of Boron fill into the Germinum Crystal and makes three Covalent bond with the Ge. Crystal and one Ge $e^{\ominus}$ can not form Covalent bond with Boron atom. These Boron atom acquires an additional $e^{\ominus}$ ~~for~~ and become negative ion.

- The hole can move freely in the V.B whereas impurity ~~ion~~ fixed in a position by the Covelent bond.

- As Boron ~~accep~~ accept the an $e^{\ominus}$ ~~from~~ Ge atom. So it is called acceptor and acceptor atom create hole without Similtanouls Generation in C.B

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E bond dig. of p-type S/C

- even a small amount of Thermal Energy can make an $e^{\ominus}$ in the V.B moves in the acceptor level due to this Ea is near about Ev and Ea - Ev in nearly about 0.01 ev.
  at 0K = T
- Ea remain vacant and it behave as insulator

- At normal temp. Ea remain Saturation few $e^{\ominus}$ are excited to

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- At T near about 100K all the acceptor atom are ionised and then further increase temp doesnot produced holes. and this region is called saturated region.

- holes conc^{n} in V.B is equal to conc^{n} of acceptor atom

$$p \cong N_A$$

- At T > 100K some $e^{\ominus}$ are exited from V.B to C.B. ~~It means~~ In C.B

- In V.B there are two types of holes
(i) due to acceptor atom ionisation
(ii) by intrinsic Process.

- At high temp. material behave as an intrinsic s/c

$$\boxed{p = n_i = n}$$

- In P-type s/c holes are majority charge carriers and they are independent of temp. in the depletion region

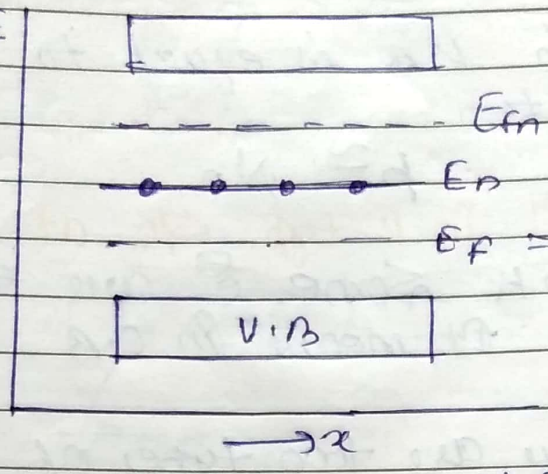
- Current in P-type s/c is mainly due to holes

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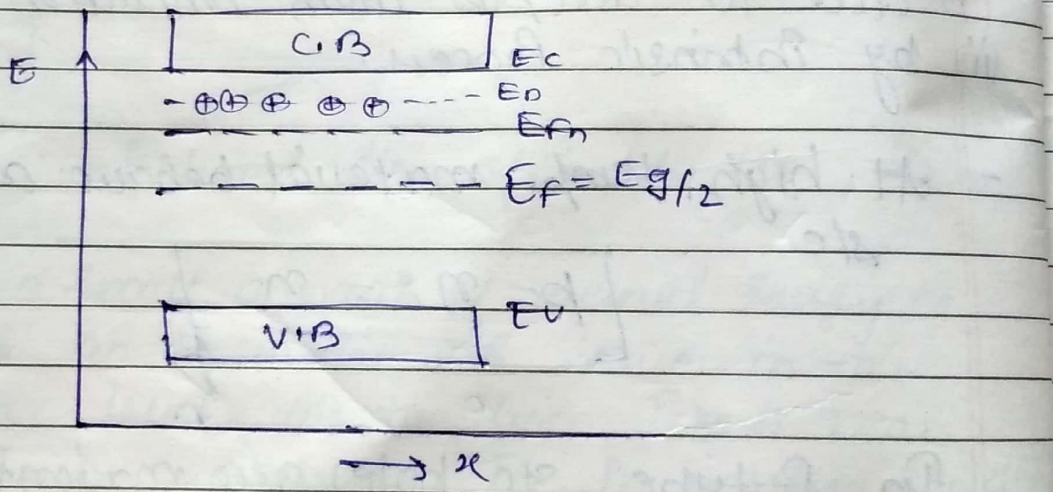
* Energy band diagram of Extrinsic at 0k and 300k :

① n type s/c :

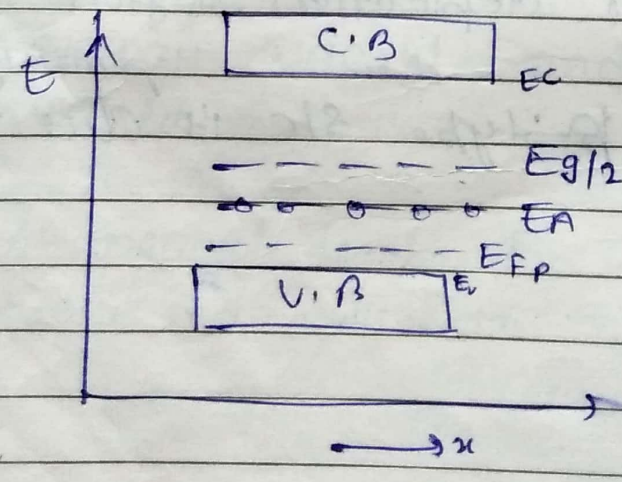
at 0k



at 300K

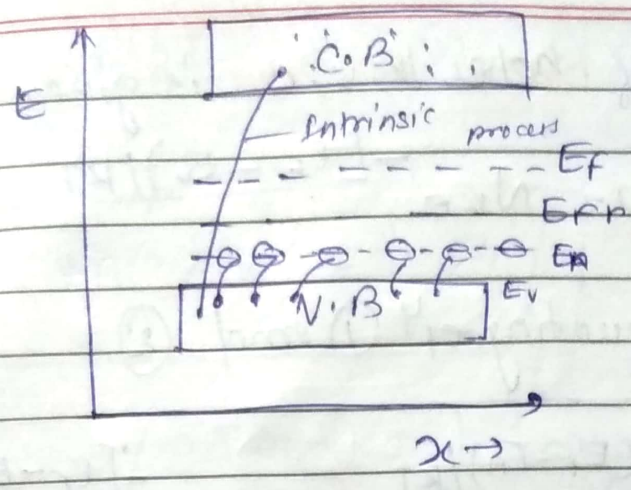


② P-type s/c :



at 300 K

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* Carrier Conc^n in P-type S/c at low temp:

Let Conc^n of acceptor in the material is N_A

- at 0K acceptor atoms are not ionised and remain at E_A

- At T > 0K acceptor atoms get ionised and holes appear in valence band.

$$p = N_A^-$$

p = Conc^n of holes in V.B

N_A^- = No. of acceptor atoms that ionised.

$$N_A^- = N_A f(E_A)$$

$$p = N_A^- = N_A \times e^{(E_F - E_A)/kT}$$

$$p = N_A e^{(E_F - E_A)/kT} \quad - (1)$$

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Conc^{n} of holes in V.B is given by

$$p = N_v e^{-[E_f - E_v]/KT} \quad \text{--- (2)}$$

Now equating eq^{n} (1) and (2)

$$N_A e^{(E_f - E_A)/KT} = N_v e^{-[E_f - E_v]/KT}$$

by taking the log of both sides and rearrange the terms

$$\left(\frac{E_f - E_A}{KT}\right) - \left(\frac{E_v - E_f}{KT}\right) = \ln \frac{N_v}{N_A}$$

$$E_f = \frac{E_v + E_A}{2} - \frac{KT}{2} \ln\left(\frac{N_A}{N_K}\right)$$

$$E_f = \frac{E_v + E_A}{2} - \frac{KT}{2} \ln \frac{N_A}{N_v}$$

$$E_f = \frac{E_v + E_A}{2} - \frac{KT}{2} \ln \frac{N_A}{2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2}} \quad \text{--- (3)}$$

at 0 K

$$E_f = \frac{E_v + E_A}{2}$$

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$$e^{(E_v - E_f)/KT} = e^{\left(\frac{E_v}{KT} - \frac{E_v + E_A}{KT}\right)} e^{\ln\left[\frac{N_A}{2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2}}\right]^{1/2}}$$

$$\boxed{p = N_v \exp\left[\frac{E_v - E_A}{KT}\right]}$$

$$p = 2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2} \exp\left[\frac{E_v - E_A}{2KT}\right] \left[\frac{N_A}{2\left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/2}}\right]^{1/2}$$

$$p = (2N_A)^{1/2} \left(\frac{2\pi m_h^* KT}{h^2}\right)^{3/4} \exp\left[\frac{E_v - E_A}{KT}\right]$$

It represent the majority charg carriers in p type s/c

Extrinsic Conductivity :

(1) Conductivity of n-type s/c is given by

$$\sigma_n = n_n e \mu_e + p_n e \mu_h$$

$n_n \Rightarrow$ conc^n of $e^\ominus$ in s/c

As in n-type s/c. $p_n << n_n$

$$\sigma_n = n_n e \mu_e$$

$$\& \; n_n = N_D$$

$$\boxed{\sigma_n = N_D e \mu_e}$$

Fermi level in Extrinsic s/c

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(2) Conductivity for P-type s/c

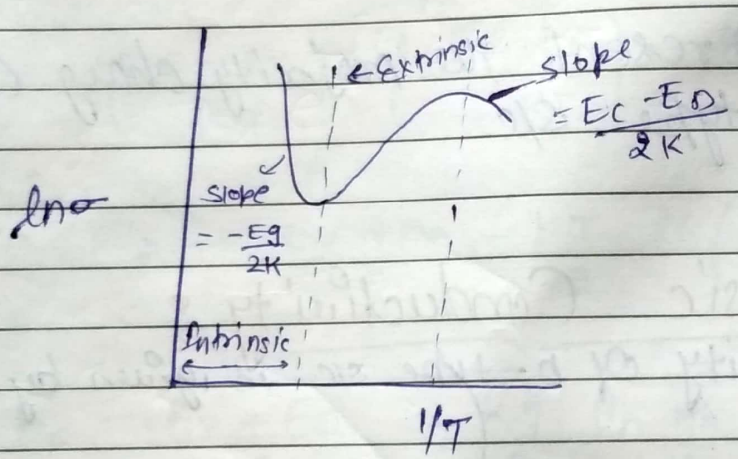
$$\sigma_p = n_p e \mu_e + p_p e \mu_h$$

$$p_p >> n_p$$

$$p = p_p e \mu_h$$

$$p_p = N_A$$

$$\boxed{\sigma_p = N_A e \mu_h}$$



It shows the variation of σ with T in s/c

* Mass action law :

Conc^n of free $e^\ominus$ and holes are always equal in an Intrinsic s/c.

- $n_i = n = p$
- When n-type impurities is added to an Intrinsic s/c Conc^n of $e^\ominus$ increased similarly by adding a p-type impurity Result in Reduction of free electrons

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- Under thermal eqb. Products of conch of free $e^{\ominus}$ and holes is constant as is independ of amount of doping by donor or acceptor impurities this is known as mass action law.

- Same is applicable for intrinsic s/c.

* Fermi Level in Extrinsic Semiconductor:
As carriers conch. in extrinsic s/c varies with temperature and impurities of conch. is added. So, the probability of occupancy of respective bands varies and consequently the position of fermi level changes with temp. and impurity conch.

In n type s/c

$$n = N_D \quad -(E_c - E_f)/KT$$

$$n = N_D = N_c e$$

or $$-(E_c - E_f)/KT$$

$$N_D = N_c e$$

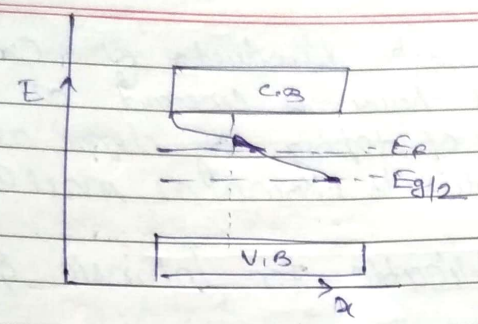
taking the log

$$\log N_D = \log N_c - \frac{(E_c - E_f)}{KT}$$

$$\log \frac{N_D}{N_c} = \frac{E_f - E_c}{KT}$$

$$E_f = E_c - KT \log\left(\frac{N_c}{N_D}\right)$$

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Now

In P type s/c

no. of Acceptor atom > no. of donor atom and conc^n. of hole is given by

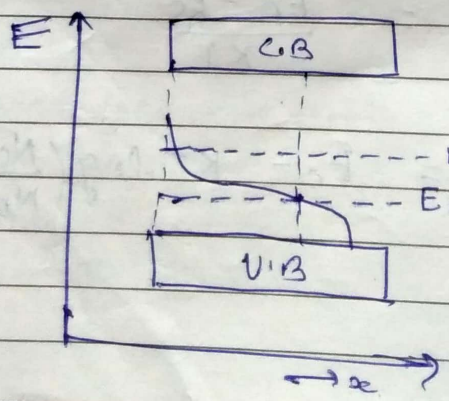
$$p = N_v e^{-[E_F - E_v]/KT}$$

taking the log of both side

$$\log p = \log N_v - \frac{[E_F - E_v]}{KT}$$

$$\log \frac{p}{N_v}$$

$$E_f = E_v + KT \ln\left(\frac{N_v}{p}\right)$$



At a
and
transfer o
Ooy é
Acceptor

So, at
thermally

As E_F
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Calculat
Conc^n ÷
In n

majorities

minority

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At a temp. Acceptor atoms get ionised and V.B filled with holes created by transfer of electron to the Acceptor atom Or $\bar{e}$ can easily move from V.B to Acceptor Energy level as compare to E_c

So, at that temp. no. of holes-$\bar{e}$ pair generated thermally decreases.

As E_F representing Probability of occupancy of Allowed Energy state. So E_F must be closer to V.B.

* Calculation of Minority charge Carriers

Conc^n :

n_n n type $\Rightarrow$ majority charge carrier

$$n_n = N_D$$

majorities $\rightarrow n_n \cdot p_n = n_i^2$

$$p_n = \frac{n_i^2}{N_D}$$

minority

$$p_n = \frac{n_i^2}{n_n}$$

Drift current: When an electric field is applied across a s/c the charge carriers aquire in dir^n motion over and above the thermal motion and Produce Drift current.

e^- in conducting band Produced Drift current denisity.

$$J_e = n e \mu_e E$$

and holes in V.B Produced the drift ~~velocity~~ density.

$$J_h = p e \mu_p E$$

then total drift current

$$J = J_e + J_p$$

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$J_{drift} = (p\mu_p + n\mu_e)\varepsilon$

drift current occurs only when External Electric field is present across in the solid.

diffusion current:

In case of s/c current in absence of E.f a spatial variation of carriers conc^n or carrier density is found in the s/c

and current start to flow in it.
if we consider and arbitary volume or arbitary surface in a volume of a solid and if there is more charge carriers on one side then the other side or we can say that there is a conc^n gradient in the material.

due to the conc^n gradient a directional moment of carriers which continue until all the carriers are equally distributed throughout the material. any moment of charge carriers constitutes an electric current and this type of moments produced a current component known as diffusion current

diffusion current $\propto$ Conc^{n} of gradient
$\propto$ rate of change of conc^{n}
of charge density

the current density due to $\bar{e}$ diffusion is equal to

$$J_e = e D_e \frac{dn}{dx}$$

(D_e ← donor density)

$$J_e = e N_D \frac{dn}{dx}$$

and due to holes

$$J_h = -e D_p \frac{dp}{}$$

BS Verma

UNIT-3

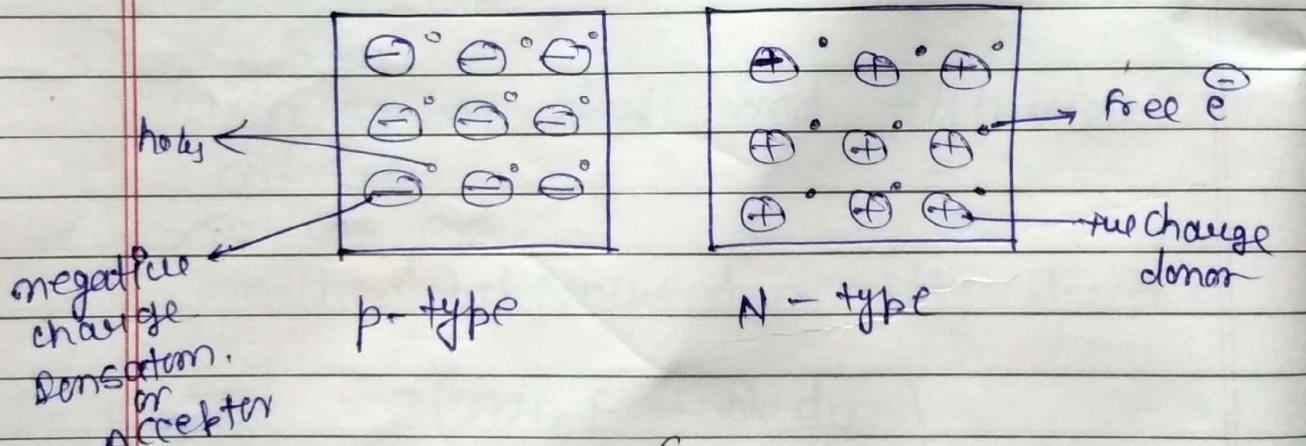
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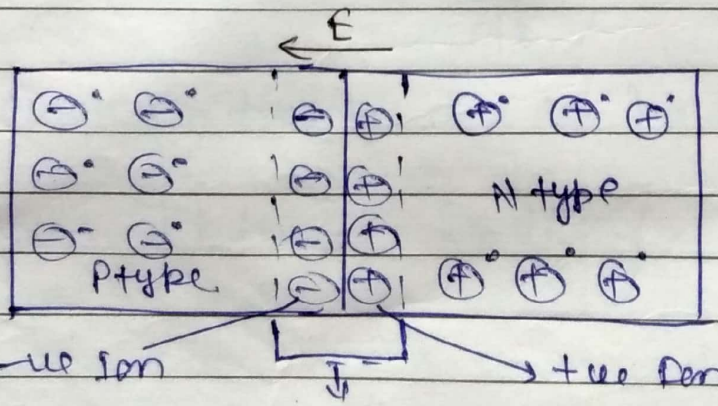
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PN Junction

PN Junction is formed from a piece (wc) by diffusing p type material to one half side and n type material to another half side. plane dtg divided by two zones is known as PN Junction

P type s/c has negative acceptor ions and positive charge free holes which move on the p side similarly n type s/c has positive donor atoms and free electrons which move about n side





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P region has large conc^{n} of holes and n region has large conc^{n} of $\bar{e}$ due to this conc^{n} difference holes diffuse from p to n side and $\bar{e}$ diffuse n to p side this process is known as diffusion

these diffuse $\bar{e}$'s and holes terminate their existance by recombination.

Due to recombination process free and mobile $\bar{e}$ and holes a large no. of positive ion forms in the n region near the junction and similarly a layer of negative ion in p region near the junction

Now the negative ion on p side repeal the $\bar{e}$'s and positive ion on n side repeal the holes. In this way a barrier is developed which is known as potential barriers due to this barrier formation after a short time diffusion proces stop and eqb achieved.

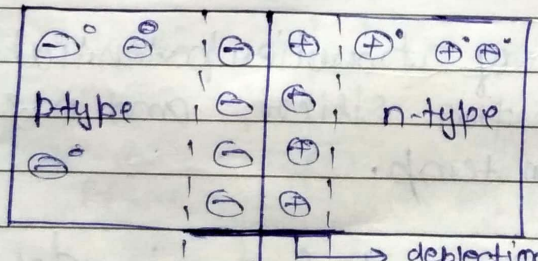
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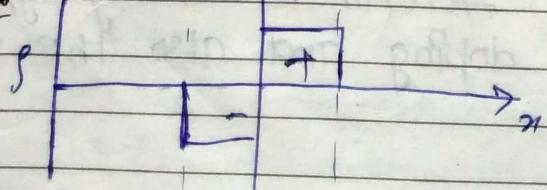
* Variation of Importance of potential barrier:
potential barrier does not allowed electron and holes to cross the junction and if we want that charge carriers cross the junction then an external voltage of appropriate potential has to be applied in order to overcome the opposition of Barrier potential

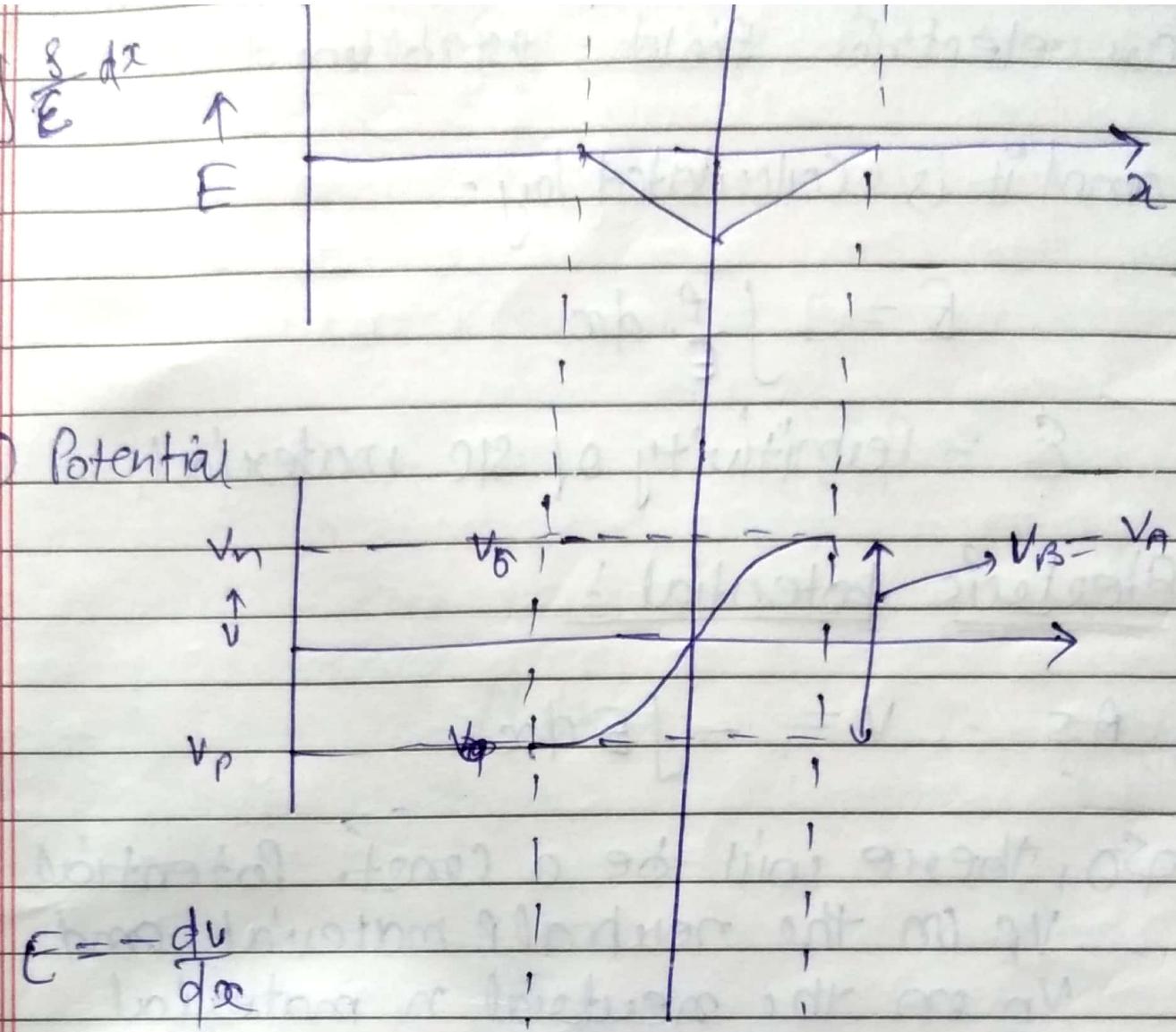
The following factors desiding the barrier potential
1. Sic material based
2. Intrinsic conch of Silicon and bie before doping
3. Level of doping
4. temp.

* Variation of charge density Electric field intensity and potential with in depletion layer:-



① ρ-charge density:-





$$E = -\frac{dv}{dx}$$

$$V = -\int E dx$$

Space charge density contains negative ions in P region and positive in n region because the charge density negative in depletion region in p side

and $\rho = 0$ at the junction.

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layer. In this way there will be electric flux lines from Right to left or electric field established.

and it is calculated by-

$$E = \int \frac{\rho}{\varepsilon} dx$$

ε = Permitivity of SC material.

(3) Electric potential :

As $V = -\int E dx$

so, there will be a const. Potential V_p on the neutral p material and V_n on the neutral n material

then $V_B = V_n - V_p$

i.e known as contact potential.

and it is Given by

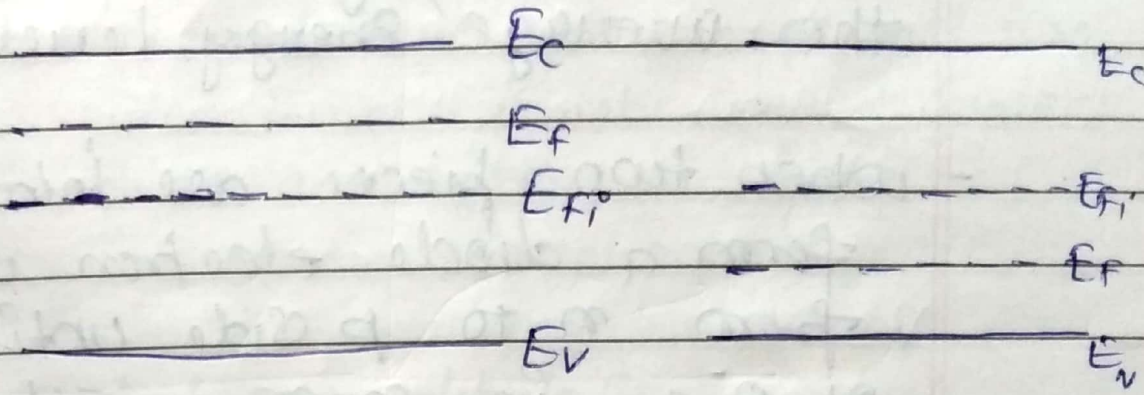
$$V_B = V_n - V_p$$

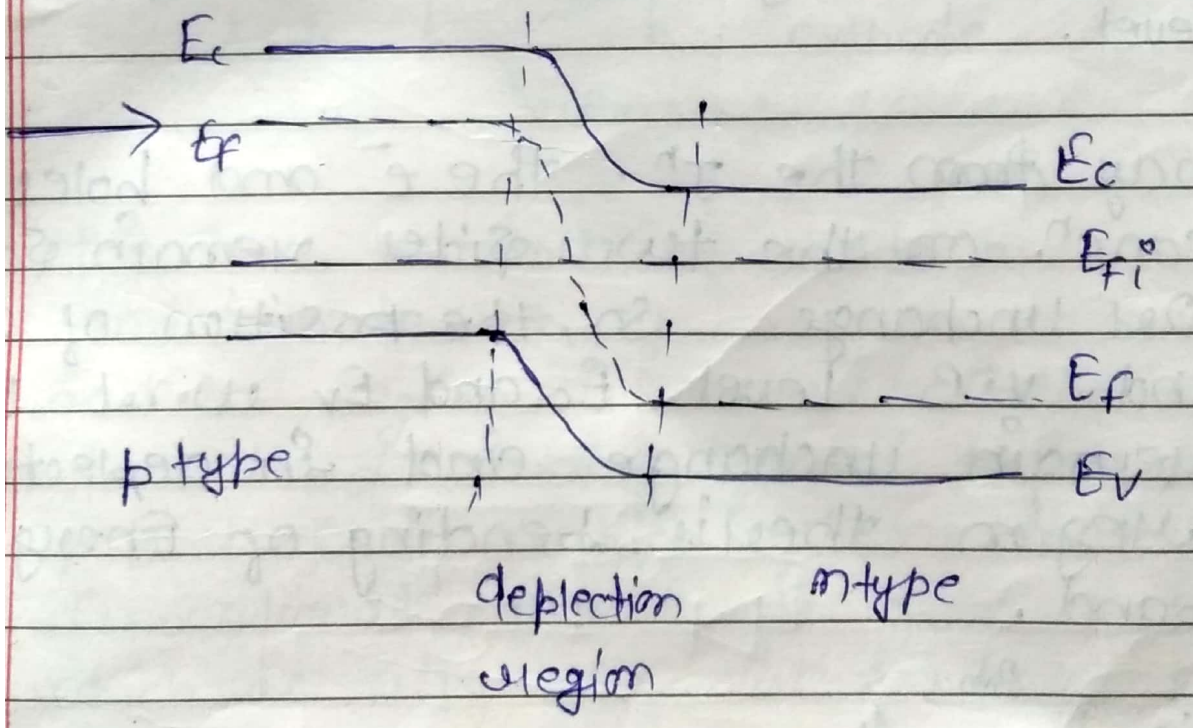
due to influence of Strong Electric field set up by the barrier potential when external electric field is equal to zero then no mobile charge carriers cross the junction or we can say

$$J_{p\,diffuse} + J_{p\,drift} = 0$$

$I_{n\,diffusion} + I_{n\,drift} = 0$

Energy ban diagram of P-N Junction





P-N Jn under thermal equilibrium

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As in n-type s/c E_f is close or near the E_c so, that electrons are occupying the higher energy level whereas fall of E_f shows the decrease the Energy content of electron or we can say that E_f indicates the average energy level

when two pieces are join together to form a diode electron will transform from n to p side untill avg. energy of e's in n or p side is same as E_f represent the avg. Energy of electrons. So, they are trying to aline together or at the same Level.

Away from the J^n. the e^- and holes Conc^n. on the two sides remain same or unchange. So, the position of C.B and V.B Level E_c and E_v w.r.t E_f remain unchange and in depletion region there is bending of Energy band.

Biasing of
1) what is Biasing, type,

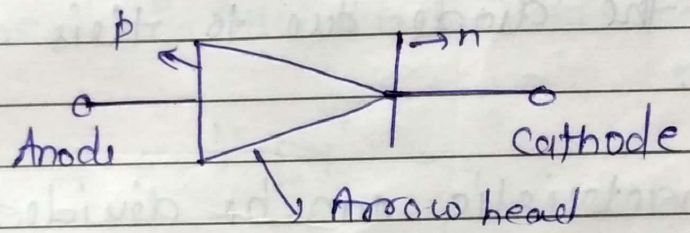
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* P-N Junction Diode:

A P-N Junction is known as P-N Junction diode or s/c diode. This is also known as crystal diode. because it is found in a crystal (Si or Ge).

a p-N junction diode a unidirectional two terminal s/c device which conduct current only in one dirn and offers a higher resistance in other direction.

* Crystal symbol of a diode:



the two terminals of diode are called anode and cathode. the p region is called anode and n-region is called cathode, Arrow head in the symbol points from p to n side which shows that dirn of conventional current is from p to n side which is also the dirn of holes current or flow of holes

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* V-I characteristic of p-N ojn diode :

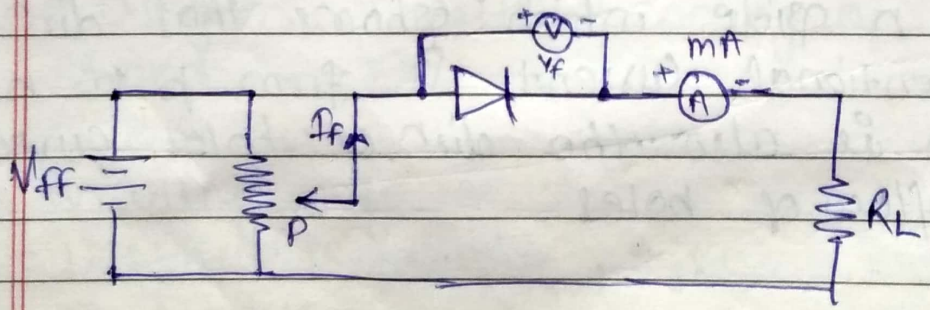
If diode is used in an electrical circuit it is imp. to know that how it response or behave in electric circuit this type of information may be ~~know~~ obtained by a curve known as volt ampere or V-I characteristic of a particular diode.

V-I characteristic of a diode is simple a curve b/w voltage applied ~~its~~ across its terminal or current that flow thrugh the diode due to this applied voltage.

V-I characteristic can be divided in to two parts

(i) forward characteristic
(ii) reverse "

(i) forward characteristics :



- The diode in the circuit is forward bias because battery Vff is pushing

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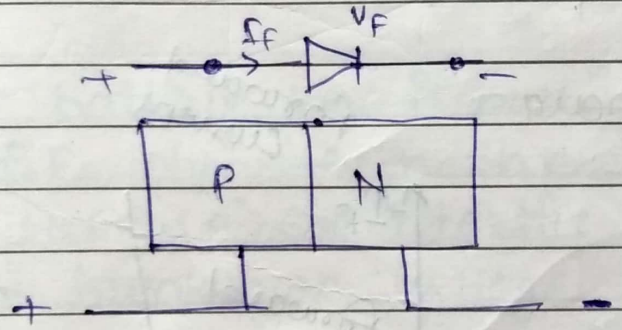
the current in dirn of arrow head.

Battery V_{ff} is connected to the diode through the potentometer (P). Potentometer (P) helps in varying the voltage across the diode.

Load Resistence (R_L) is used in the circuit to limit current through the diode.

A voltmeter is connected across the diode to measure the voltage

A Ammeter is connected to measure current in the circuit.



Forward characteristics

The voltage across the diode increases greadually and corresponding increase in current is noted the graph is ploting by taking voltage along the x-axis and current along the Y-axis.

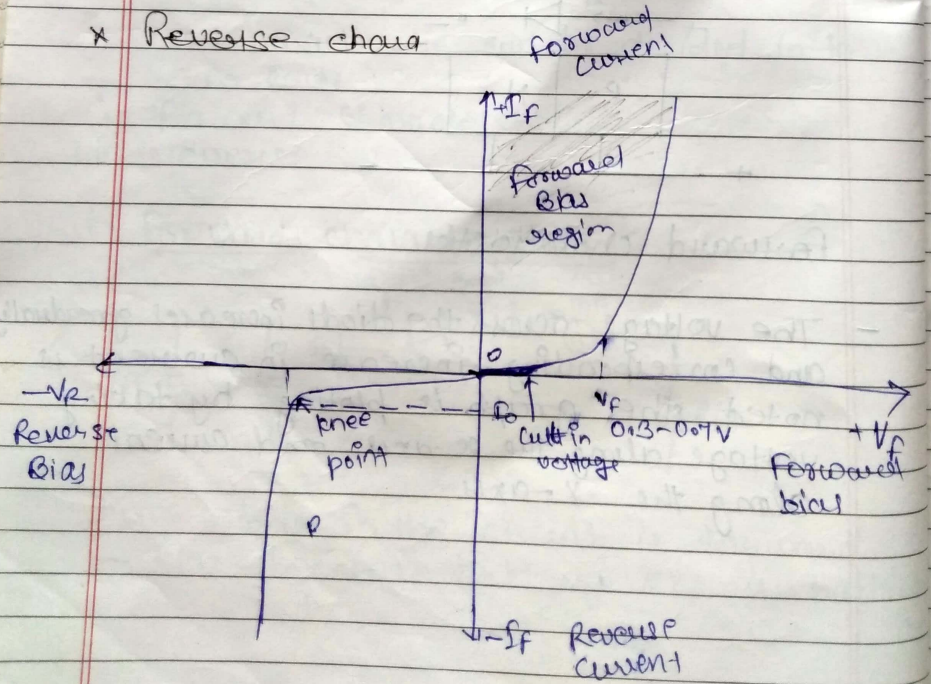
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from the graph, It is seen that upto a point current is very small and this is due to the applied voltage has to overcome the potential barrier. So, in this region diode conduct Poorly

- once applyed voltage is increases then it overcome the potential barrier and current increases rapidly this voltage at which current increase rapidly is known as knee voltage and it is denoted by V_0

$V_0 = 0.3$ for Ge
$= 0.7$ for Si.

* Reverse chara



The battery V_{RR} is pushing the current in dir opposite to the arrow head the reverse characteristics shows that below breakdown voltage diode current is very small and almost cons. this current is known as reverse saturation current and denoted by I_o

I_o is of the order of μA for Ge and nA for silicon diode.

Reverse saturation current is due to the moment of minority charge carriers which are thermally generated so I_o does not dep is depend on temp.

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and does not depend on Reverse bias voltage.

* Breakdown voltage:
It is the minimum reverse voltage at which P-N jn breakdown with sudden increase in current in Reverse dirn.

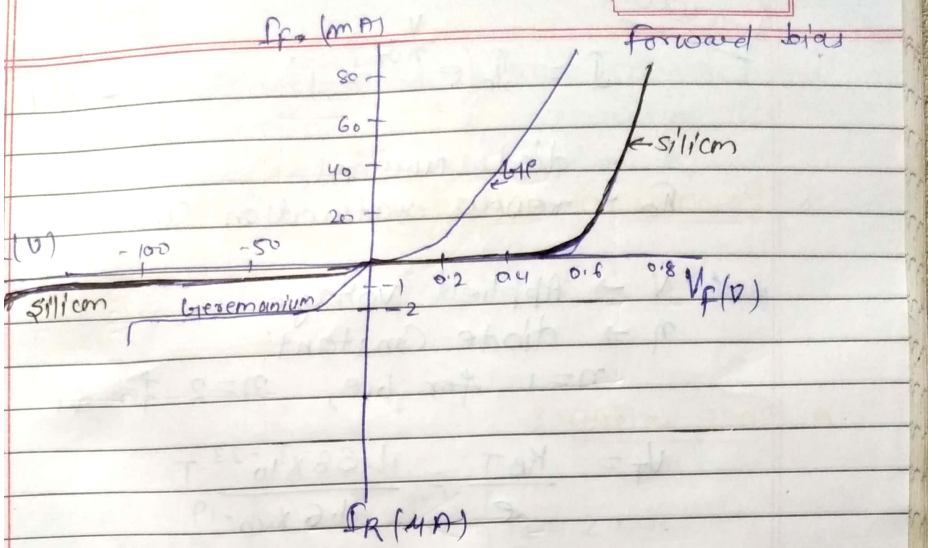
* Knee voltage: In forward bias to P-N jn a very small current flow until the forward voltage exceeds the jn barrier potential. This forward voltage at which current through the jn is start increasing rapidly is known as knee voltage or cut in voltage.

* P-Inverse voltage:
It is max. reverse voltage that can be applied to P-N jn diode without damage the jn.

- If reverse voltage exceeds the its Peak Inverse voltage jn may get destroyed due to over heating.

* V-I characteristic for Ge and Si.:

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knee volt.

Cut in voltage for Si is 0.6 volt
and " Ge is 0.2 volt.

The breakdown voltage for Si is higher then that of Ge. because Si can with stand to a higher reverse voltage.

Reverse saturation current I_0 for Ge is in μA and for Si nearly in nA at room temp.

Diode current eqⁿ. :

In solid state phy. diode current eq⁴, relating voltage and current for forward bias and reversed bias can be given by -

I = diode current
I_0 = reverse saturation current

V → Applied voltage
η → diode Constant
$\eta = 1$ for Ge, $\eta = 2$ for Si.

Q.

$$V_T = \frac{K_B T}{e} = \frac{1.38 \times 10^{-23} T}{1.6 \times 10^{-19}}$$

$$V_T = \frac{T}{11,600}$$

at Room temp $T = 300K$.

$V_T = 26mV$

$$I = I_0 \left[e^{40V/\eta} - 1 \right]$$

for Ge $\eta = 1$

$$I = I_0 \left[e^{40V} - 1 \right]$$

for Si $\eta = 2$

$$I = I_0 \left[e^{20V} - 1 \right]$$

Find V_F, V_R and I_F

(i) $V_F = 0.7\ V$

Rectifiers,

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* Rectifiers:
A rectifier is a circuit which is used to convert AC voltage into pulsating DC voltage

there are two types of rectifier is used
(i) half wave rectifier [HWR]
(ii) full wave rectifier [FWR]

(i) Half wave rectifier: [HWR]
(ii) In HWR rectify conducts current only during the positive half cycle of, AC supply

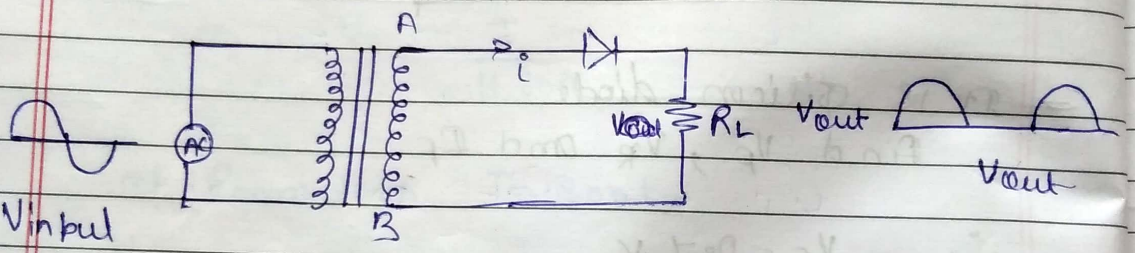
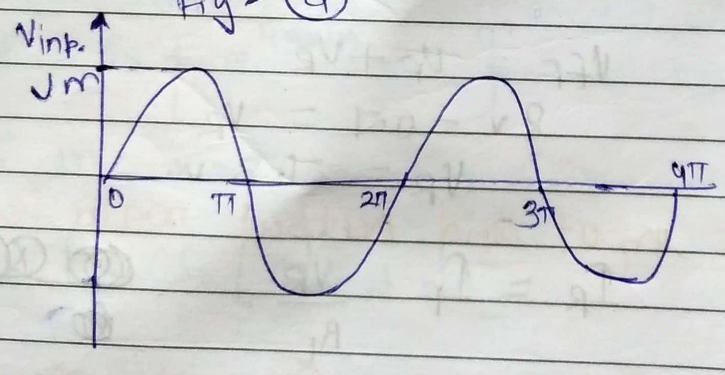


Fig- (a)



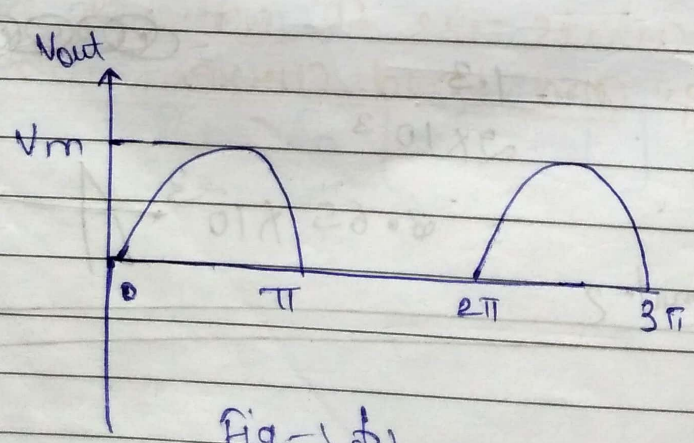


Fig-(b)

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(iii) The negative half of AC supply are suppressed as there is not current conduct and hence no voltage appears across the load.

* Circuit details:

- circuit has a single crystall diode which acts as a half wave rectifier

- The AC supply to be rectified is applied in series with the diode and load resistance R_L.

- AC supply generally giving through a transformer as there are two advantages of transformer
  (i) It allows to step up or step down the AC input voltage as the situation demands
  (ii) Transformer isolates the rectifier circuit from power line and thus reduce the risk electric short.

- The input and output waveform of rectifier. (Fig-b)

- To calculate the DC value of output voltage and load current for HWR:

$V_o = V_m \sin \omega t$ for $0 \leq \omega t \leq \pi$

$V_o = 0$ for $\pi \leq \omega t \leq 2\pi$

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Dc value or avg. value of o/p voltage is expressed as

$$V_{avg.} = V_{dc} = \frac{\text{Area under the curve over full cycle}}{\text{Base}}$$

$$\text{Area} = \int_0^{2\pi} V_0 \, d(\omega t) = \int_0^{\pi} V_0 \, d(\omega t) + \int_{\pi}^{2\pi} V_0 \, d(\omega t)$$

$$= \int_0^{\pi} V_0 \sin\omega t \, d(\omega t) + \int_{\pi}^{2\pi} 0 \cdot d(\omega t)$$

$$\text{Area} = V_m \left[-\cos\omega t \right]_0^{\pi} + 0$$

$$\text{Area} = V_m \left[-\cos\pi - (-\cos 0) \right]$$

$$= 2V_m$$

$$V_{dc} = \frac{2V_m}{2\pi} = \frac{V_m}{\pi}$$

$$\boxed{V_{dc} = 0.318 V_m}$$ — learn

Similarly

$$I_{dc} = \frac{V_{dc}}{R_L} = \frac{2V_m}{\pi R_L} = \frac{2I_m}{\pi}$$

$$\boxed{I_{dc} = 0.318 I_m}$$

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The above calculation is consider by assuming that diode resistance in forward biase is zero.

then if forward Resistane R_f is taken

$$V_{dc} = \frac{V_m}{\pi} - I_{dc} R_f$$

$$I_{dc} = \frac{V_m}{\pi [R_L + R_f]}$$

* Peak inverse value of voltage of half wave rectifier.

During negative cycle diode is Reverse bias and does not conduct the current so, the current in the circuit is zero and voltage across RL is also zero and hence whatever is the apply input voltage it coill appear across Reverse bias and max. value of this Reverse voltage occurs at peak of negative cycle of input voltage i.e V_m. this voltage is called peak Inverse voltage and it denoted by

$$PIV = V_m$$

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* Drawback :- (i) The Pulsating current in the load contains Alternating components whose basic freq. is equal to supply freq. so, an adequate filtering is required to produce steady direct current.

(ii) AC supply delivers Power only during the half time, so output is Low

(iii) circuit have Low transformer utilization factor. which shows transformer is not completely utilize.

(iii) Efficiency of rectification is also Low which is equal to 40%. theoritically but actual practice value is less then

*

* Repell factor (γ):-

It is given by rms value of AC comp. of o/p

$$\gamma = \frac{\text{rms value of ac component of o/p}}{\text{dc component of o/p}}$$

V_{rms} = rms value of ac component
V_{dc} = avg. or dc component
I_{rms} = rms value of ac component
I_{dc} = dc value of load current

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Output voltage or load current of a rectifier contains two components mainly dc component and ac component. ac comp. present in output is called a ripple this ripple accounts for pulsations in the output of rectifier and are undesirable so, effectiveness of a rectifier depend on magnitude of ripple in output is smaller in ripple more effectively is the rectifier.

methamatically ripple factor is calculated by

$$\gamma = \frac{V_{rms}}{V_{dc}} = \frac{I_{rms}}{I_{dc}}$$

$$I_{rms} = \sqrt{I_{ac}^2 + I_{dc}^2}$$

$$I_{ac} = \sqrt{I_{rms}^2 - I_{dc}^2}$$

$$\gamma = \frac{I_{ac}}{I_{dc}} = \frac{\sqrt{I_{rms}^2 - I_{dc}^2}}{I_{dc}}$$

$$\gamma = \sqrt{\left(\frac{I_{rms}}{I_{edc}}\right)^2 - 1}$$

this is the general expression for ripple factor

For Half wave:

$$\gamma = \sqrt{\left(\frac{I_m/2}{I_m/\pi}\right)^2 - 1}$$

$\eta = 1.21$

* Rms load current (I_{rms}) of HWR :

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} i_L^2 \, d(\omega t)}$$

$$I_{rms} = \sqrt{\frac{1}{2\pi}\left[\int_0^{\pi} i_m^2 \sin^2\omega t \, d(\omega t) + \int_{\pi}^{2\pi} 0 \cdot d(\omega t)\right]}$$

$$I_{rms} = I_m\sqrt{\frac{1}{2\pi}\int_0^{\pi} \frac{1-\cos 2\omega t}{2} \, d(\omega t)}$$

$\left(\frac{I_m}{2\pi}\right)$

$\left(\frac{I_m}{2\pi}\right)\cdot\frac{1}{2}$ $\quad \frac{1}{2}\cdot\cos 2\omega t$ $\quad \frac{1}{2}$

$$I_{rms} = I_m\sqrt{\frac{1}{4\pi}\left[(\pi-0)-(0-0)\right]}$$

$$I_{rms} = \frac{I_m}{2}$$ Rms load current of HWR.

* Efficiency of rectification :
It is defined as the ratio of dc power delivered to load to AC input power from secondry wdg of transformer

$$\eta = \frac{\text{Output dc power}}{\text{input dc power}}$$

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$$\eta = \frac{P_{dc}}{P_{ac}}$$

$$\eta = \frac{I_{dc}^2 \times R_L}{I_{rms}^2 (R_L + R_f)}$$

For HWR

$$\eta = \frac{I_m^2/\pi^2 \times R_L}{\frac{I_m^2}{4}(R_L + R_f)}$$

$$= \frac{4}{\pi^2} \frac{R_L}{(R_L + R_f)}$$

$$\boxed{\eta = \frac{0.406}{\left(1 + \frac{R_f}{R_L}\right)}} \quad (1)$$

η will be max. if $R_L >> R_f$

$$\eta_{max} = 0.406 = 40.6\%$$

* Transformer utilization factor: (TUF):
It is defined as the ratio of dc power delivered to the load to and AC rating of transformer secondly.

$$TUF = \frac{\text{dc Power to load}}{\text{ac Power rating of transformer}}$$

$$TUF = \frac{I_{dc}^2 R_L}{V_{rms} \times I_{rms}}$$

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0.404

$$TUF = \frac{(0.318 I_m)^2 \times R_L}{\frac{V_m}{2} \times \frac{I_m}{2}}$$

$$= \frac{0.101 I_m^2 \times R_L}{\frac{V_m}{2} \times \frac{I_m}{2}}$$

$0.287 R_L$

=

Q. Find the transformer utilization f. for HWR.

[in Rf consider
without Rf consider]

$$TUF = \frac{\text{DC Power}}{\text{AC Power}} = \frac{V_{dc} \cdot I_{dc}}{V_{ac} \cdot I_{ac}}$$

$$= \frac{V_{dc} I_{dc}}{I_{rms} V_{rms}}$$

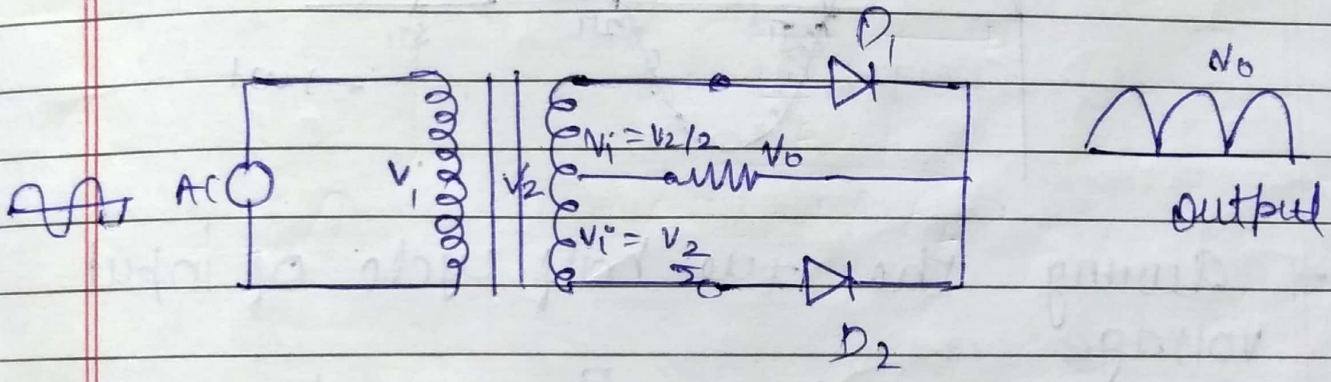
$$TUF = \frac{\frac{I_m}{\pi} \cdot \frac{V_m}{\pi}}{\frac{V_m}{2} \cdot \frac{I_m}{2}} = \frac{4}{\pi^2}$$

$$TUF = 0.406 = 40\%$$

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* full wave Rectifier:
In full wave rectifier current flow through the load in same dir^n for both cycles of AC input voltage. this can be achieved by using two diodes in conducting conditions alternately there are two types of full wave rectifier
(i) centretape full wave rectifier
(ii) bridge full wave rectifier

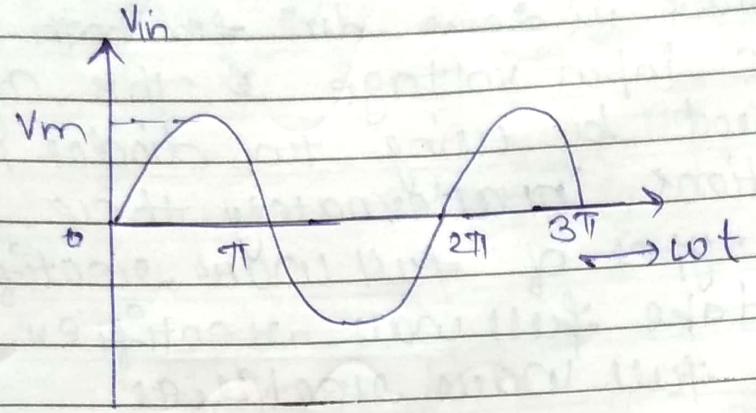
(i) centre tape full w R:
Two diodes D_1 and D_2 are connected to centre tape secondry wdg of transformer

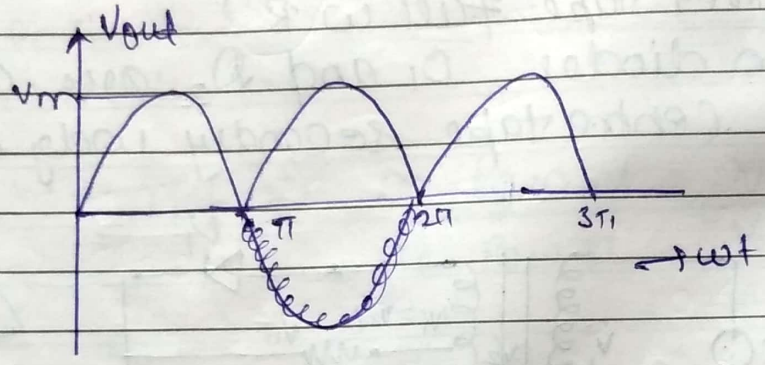


- input voltage is applied to the primary of transformer the voltage b/w one end of secondry and centre tape is equal to half of secondry voltage it means if applied voltage across primary is V and across secondary is

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Working:





- during the +ve half cycle of input voltage

  let v_i be the instantanious value of voltage across secondary then v_i is equal to $V_m \sin \omega t$

$$v_i = V_m \sin \omega t$$

- for +ve cycle diode D_1 is forward bias and D_2 is reverse bias Hence D_1 conducts and D_2 is in cutoff positi a current I_L flow through R_L producing output voltage V_o

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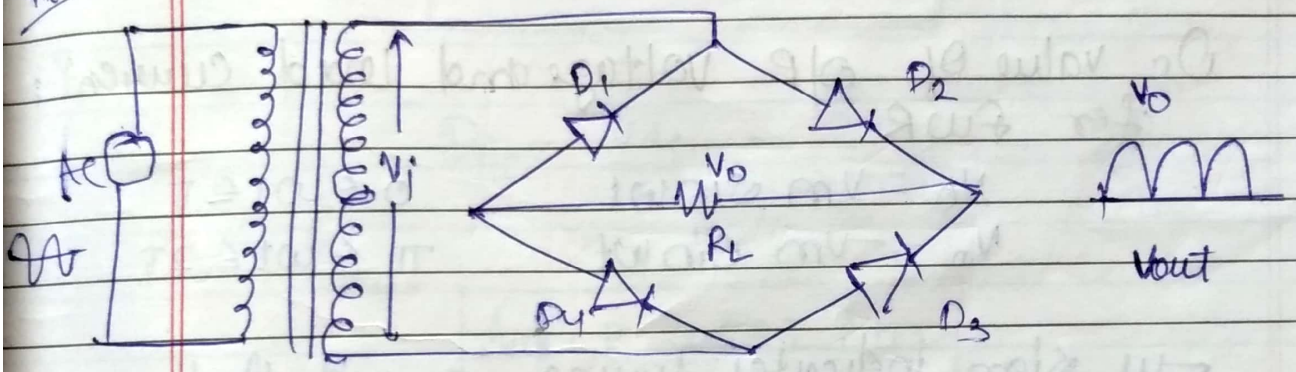
- during negative half cycle D_1 is reverse bias and D_2 is forward bias hence D_1 is in cut off position and D_2 is forward bias.

flow through R_L Producing Output voltage V_o

* Full wave Bridge Rectifier :

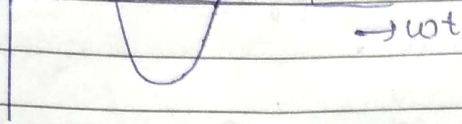
Bridge Rectifier uses four diodes which are connected across secondary of transformer

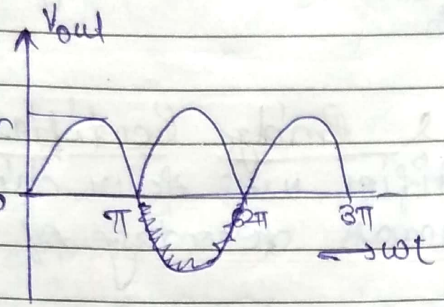
Low Power Loss
High efficiency



- During +ve half cycle D_2 and D_4 are in F.B condn and they conduct and output voltage develop across the resistor R_L

- During -ve half cycle D_1 and D_3 are F.B and conducts D_2 and D_4 are reverse Bias and in cut off position and output voltage obtain (V_L)





* Dc value of o/p voltage and load current for FWR

$V_o = V_m \sin\omega t \quad 0 \le \omega t \le \pi$

$V_o = -V_m \sin\omega t \quad \pi \le \omega t \le 2\pi$

-ve sign indicates during second half cycle, since wave is inverted

$V_{avg} = V_{dc} = \frac{\text{Area under the curve over full length}}{\text{Base}}$

$$\text{Area} = \int_0^{\pi} V_o \, d(\omega t) + \int_{\pi}^{2\pi} V_o \, d(\omega t)$$

$$= \int_0^{\pi} V_m \sin\omega t \, (d(\omega t)) + \int_{\pi}^{2\pi} -V_m \sin\omega t \, d(\omega t)$$

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$$= [-V_m \cos \omega t]_0^{\pi} + [V_m \cos \omega t]_{\pi}^{2\pi}$$

$$= V_m[-\cos\pi - \cos 0] + V_m[\cos 2\pi - \cos\pi]$$

$$= V_m[+1+1] + V_m[1+1]$$

Area = $4V_m$

$$V_{dc} = \frac{4V_m}{2\pi} = \frac{2V_m}{\pi}$$

$$\boxed{V_{dc} = 0.636\ V_m}$$

$$I_{dc} = \frac{V_{dc}}{R_L} = \frac{2V_m}{\pi R_L} = \frac{2I_m}{\pi}$$

$$\boxed{I_{dc} = 0.636\ I_m}$$

Peak inverse voltage (PIV):
~~centre tap~~ FWR: During the +ve half cycle diode D_1 conducts and D_2 cut off if

$V_i = V_m \sin \omega t$

where V_m is the max. or peak value across half secondary wdg

D_1 is F.B and offer almost zero Resistance so, Peak voltage V_m appears across R_L

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- D_2 in Reverse Bias and total voltage across D_2 is sum of voltage V_m across lower half of secondry and V_m across R_L i.e.,

$$PIV = 2V_m$$

(ii) for Bridge Rectifier:
Diode D_1 and D_3 are not conducting where as D_2 and D_4 are conducting the voltage drop across D_2 and D_4 may be assumed zero bcz they are in F.B conditions

The reverse voltage across non conducting D_1 and D_3 is equal to V_m i.e.,

$$PIV = V_m$$

* RMS Value of Load Current of FWR (I_{rms}) *

$$I_{rms} = \sqrt{\frac{1}{2\pi}\int_0^{2\pi} i_L^2 \, d(\omega t)}$$

$$I_{rms} = \sqrt{\frac{2}{2\pi}\int_0^{\pi} i_L^2 \, d(\omega t)}$$

$$I_{rms} = \sqrt{\frac{1}{\pi}\int_0^{\pi} I_m^2 \sin^2 \omega t \, d(\omega t)}$$

$$I_{rms} = I_m \sqrt{\frac{1}{\pi}\left[\int_0^{\pi} \frac{1-\cos 2\omega t}{2} \, d(\omega t)\right]}$$

$$I_{rms} = I_m \sqrt{\frac{1}{\pi}\left[\frac{\omega t}{2} - \frac{\sin 2\omega t}{4}\right]_0^{\pi}}$$

2-

$$I_{rms} = I_m \sqrt{\frac{1}{2\pi}[\pi - 0]}$$

$$\boxed{I_{rms} = \frac{I_m}{\sqrt{2}}}$$

This is rms load current of FWR.

$$\boxed{V_{rms} = \frac{V_m}{\sqrt{2}}}$$

* Ripple factor of FWR:

$$\gamma = \sqrt{\left(\frac{I_{rms}}{I_{dc}}\right)^2 - 1}$$

$$I_{dc} = \frac{2I_m}{\pi} \qquad I_{rms} = \frac{I_m}{\sqrt{2}}$$

$$\gamma = \sqrt{\left(\frac{I_m/\sqrt{2}}{\frac{2I_m}{\pi}}\right)^2 - 1}$$

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$$\gamma = \sqrt{\frac{\pi^2}{8} - 1} = 0.48$$

$\gamma = 0.482$ (FWR)
$\gamma = 1.21$ (HWR)

Hence we see ripple factor of FWR is much smaller then HWR. due to this reason it is widely used.

* Efficiency of rectification in FWR:

$$\eta = \frac{\text{output dc Power}}{\text{Input ac Power}}$$

$$\eta = \frac{P_{dc}}{P_{ac}}$$

$P_{dc} = I_{dc}^2 \times R_L$

$P_{ac} = I_{rms}^2 \times (R_L + R_f)$

$$\eta = \frac{I_{dc}^2 \times R_L}{I_{rms}^2 (R_L + R_f)}$$

$$\eta = \frac{\frac{4I_m^2}{\pi^2} \times R_L}{\left(\frac{I_m}{\sqrt{2}}\right)^2 \times (R_L + R_f)}$$

$$\eta = \frac{8}{\pi^2} \frac{R_L}{(R_L + R_f)}$$

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$$\eta = \frac{8}{\pi^2} \cdot \frac{R_L}{(R_L + R_f)}$$

$$\eta = \frac{0.812}{1 + \frac{R_f}{R_L}}$$

η will be max. if $R_L >> R_f$

$$\eta_{max} = 0.812 = 81.2\%$$

η for FWR = 2HWR.

* TUF of FWR :-
TUF of a centre tapped is calculated for secondry & primary coily seperately and then avg. TUF is calculated

$$\text{TUF (secondry)} = \frac{\left(\frac{2I_m}{\pi}\right)^2 R_L}{\frac{V_m}{\sqrt{2}} \times \frac{I_m}{\sqrt{2}}}$$

As $V_m = I_m R_L$

$$\text{TUF} = 0.812 = 81.2\%$$

As we know that FWR consist of 2HWR

Tuf (primary) = 2 x TUF of HWR
= 2 x 0.287
= 0.574

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Total TUF of FWR = $\frac{\text{Primary TUF} + \text{Secondry TUF}}{2}$

Total TUF for FWR = $\frac{0.574 + 0.814}{2} = 0.693$

* Breakdown mechanism : In a P-N Junction there are two types Breakdown mechanism
(i) Zener break down
(ii) Avalanche

(i) Zener break down :
(ii) zener break down occurs in zener diodes having $V_z < 5$ volt or blw 5 to 8 volt.

(ii) When a reverse voltage of 5 volt applied to a zener diode it caused a very intence Electric to appear across a narro diplection region field Intensity is tippically of the order of 3×10^5 volt/cm. Such an intense Electric field is strong to co some of the valence electron into CB by breaking covalent bond these electrons become free and avilable for Conduction.

(iii) Large no. of these free e constitute a large Reverse Curren through zener diode and breakdown occurs due to zener effect

(iv) A curr
conne
to for
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(ii) Avala
- A·B

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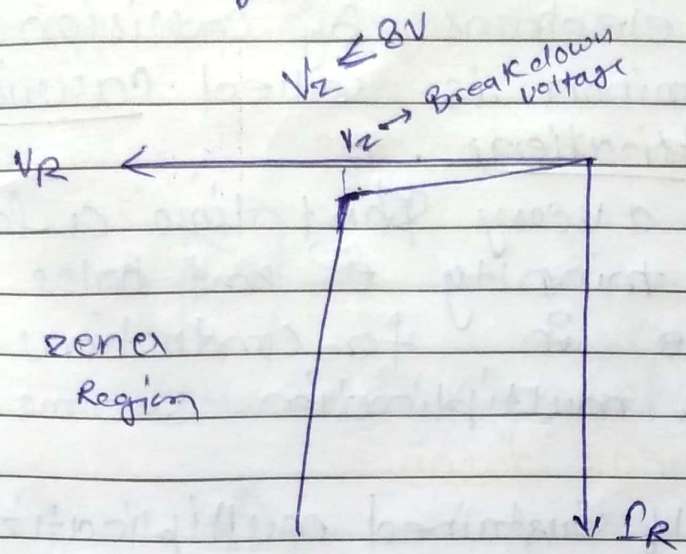
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(iv) A current limiting resistance should be connected in series with the zener diode to protect it against damage due to excess heating



(ii) Avalanche Breakdown:

- A·B occurs in zener diode with $V_Z > 8V$

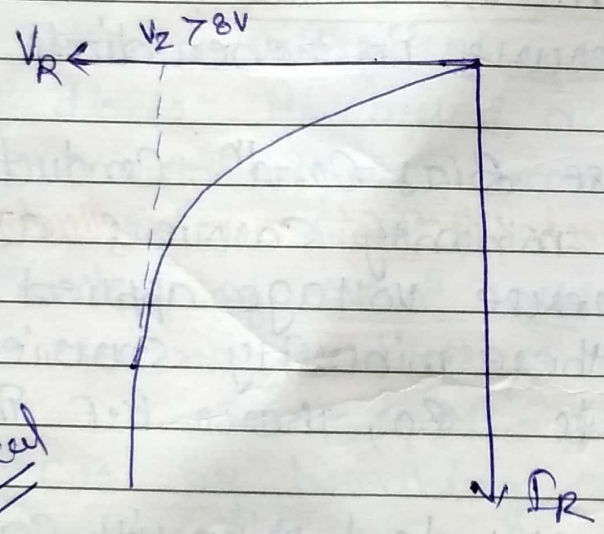
- In Reverse Bias Condⁿ. Conduction take place only due to minority carriers as we increase the reverse voltage applied to zener diode these minority carriers tend to accelerate so, there K·E increases

- These accelerated minority carriers collides with stationary atom and impart some of the K·E to valence electron Present in covalent Bond.

- Due to this additional Aquael energy these valence electron will break these covalent bond and jump to C.B.

carrier multiplication become self sustain

this self sustained multiplication is called avalanche effect



Imp Numerical

* Zener diode :

(i) It is a reverse bias heavily doped P-N junction diode which operate in breakdown region.

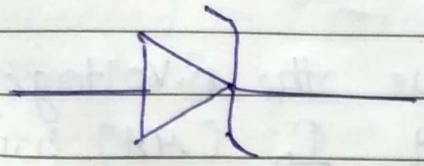
(ii) Reverse breakdown of a P-N J^n may occurs either due to zener effect or avalanch effect

V-K Method

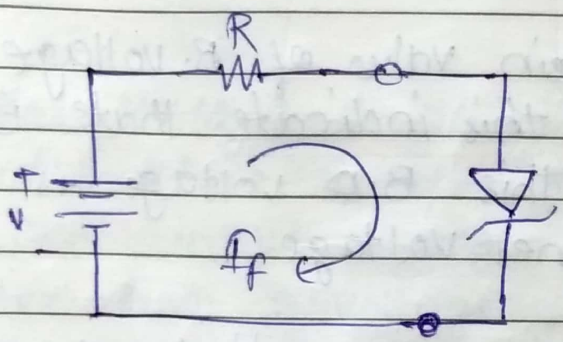
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(iii) zener effect dominant at reverse voltage < 6V whose A. Effect dominent above 6V

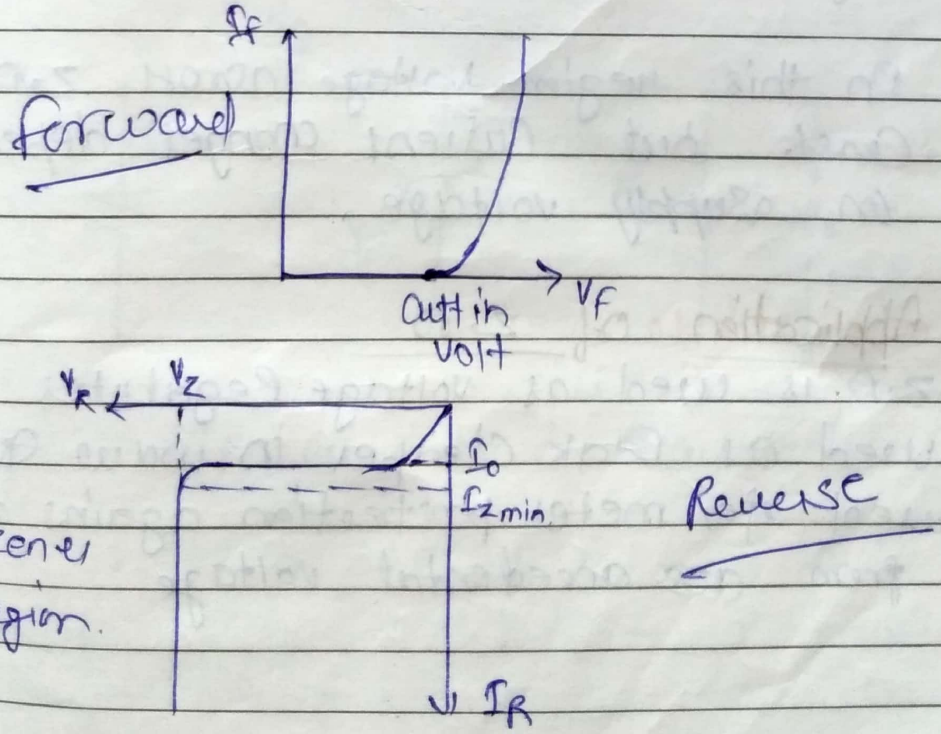
(iv) Breakdown voltage of zener by setting the dopping of



zener diode symbol



* V-I characteristic of zener diode:



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V-I characteristic are divided in two
- F. char.
- Reverse char.

* Forward char. is same as the P-N J° diode
* ~~Same as~~ ~~P-N~~ Same as

* As we increase the R. voltage initally a small current I_0 (μA) will flow due to minority carriers

* At a certain value of R. voltage I_R increase suddenly this indicate that Breakdown occurs this B.D voltage is known as ~~Zener~~ zener voltage

* After B.D zener diode operates in a region called a zener Region

On this region voltage across Z.D remains Const. but Current changes depending on supply voltage.

* Application of Z.D
* Z.D is used as voltage Regulater
* Used as Peak Clipper in wave shaping
* used for meter protection against damage from accedental voltage

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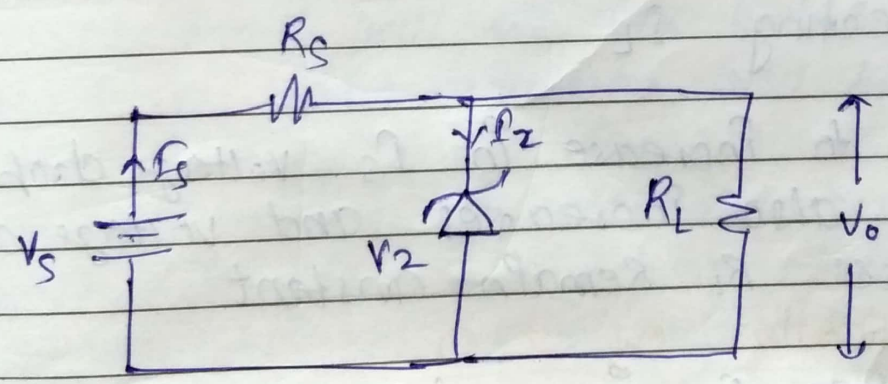
Zener diode as Voltage Regulator:

- Voltage Regulator is a circuit whose fn is to maintain a const. output DC voltage inspite of the AC input voltage fluxating or changes in Load Resistance

- this is called Shunt Regulator bcz the Z.D is connected in Parallel or Shunt with the Load Resistance

- R_s is connected to limit the current in the circuit

- Regulated Voltage is obtained across the Load Resistance R_L for the operation of the ckt input voltage V_s should be greater then z. voltage V_z only then diode operate in Breakdown region



O/p current is calculated

$$I_S = I_z + I_L$$

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$$I_S = I_Z + I_L$$

$$V_S = I_S R_S + V_Z$$

$$\boxed{I_S = \frac{V_S - V_Z}{R_S}}$$

$$\boxed{V_O = V_Z}$$

$$\boxed{I_Z = I_S - I_L}$$

* Working!

(1) Case I: Regulation when input voltage is varied!

* In this case R_L is fixed V_S is varying
* when I/P voltage is ↑es current is also ↑es
  It means $\boxed{I_S = I_Z + I_L}$ increases without effecting I_L

* Due to increase in I_S voltage drop across R also increases and voltage drop across R_L Remain constant

Case: II when R_L is variable

* In this case V_S is fixed

* when R_L ↓es I_L ↑es which causes I_L to ↓es due to this voltage drop across Rs remain const.

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and V_L is also Remain Constant.

* Drawbacks :-
* O/P voltages varies slightly due to zener Resistance (R_s)

* efficiency is low for heavy Load Current bcz there is considerable losting R_s.

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* LED (Light Emmiting Diode) :-
LED is a special type of P/C PN J^n that under F.B Cond^n can emmit external spontanious radiation (this radiation is UV, visible and infra-red region) they are widely used as visual indicator as well as moving light display.

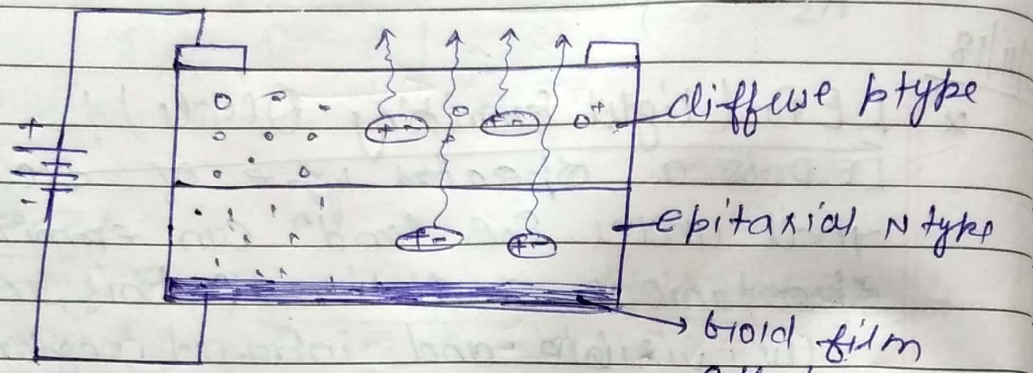
* Constructions :-
Direct Band gap P/C (ex- GaAs, GaP, GaAsP) used as light emmition and Light emitted by three Process
(i) Generation of $e^{\ominus}$ holes pair by exitation
(ii) recombination of electron holes pair
(iii) photon emites as a result of recombinations.

- Under F.B Photon generated by recombination of $e^{\ominus}$ ejected from N to holes in P side and holes ejected from P to electron of N side

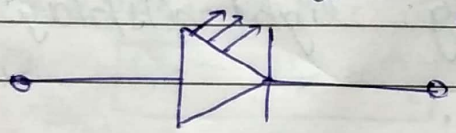
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- Efficiency of light production can be improved if current Proces crossing the Jn is predomently due to e and it can be done by increasing the mobability of e or ↑es the density of donors

$\mu_e > \mu_h$
$N_D >> N_A$



Crossing Of LED



Symbol

GaAs ⇒ Gives Visible Infrared
GaAsP ⇒ Red or Yellow
GaP ⇒ Red ~~or Oto~~ or green

- N-type ⇒ layer is grown upon a substraight ~~on~~ in P region deposite on it by diffusion

- Gold film at the bottom of the substrate used to provide cathode as well as

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to reflect light as much as possible

- Working Principle:
- It is based on the fact the called injection electroluminescence which is emmition of light from a solid with the excitation provided by an electrostatic field

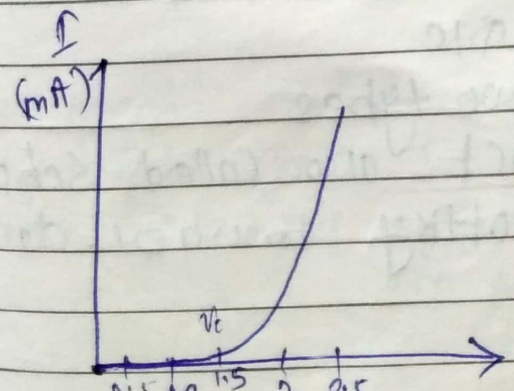
- In FB PN Jn forward current flow due to free $e^{\ominus}$ as $e^{\ominus}$ higher in CB and holes are higher in VB when current passes through PN Jn recombination of $e^{\ominus}$ holes takes place

- When $e^{\ominus}$ recombine with ↑ holes · its falls from higher energy to lower energy state by releasing a photon of wavelength corresponding to energy diff · (w transition

- Energy difference given a either in form of heat or in form of light.

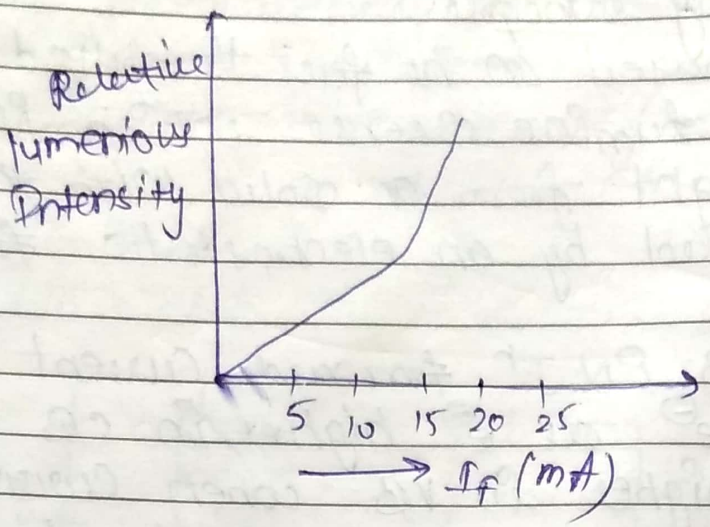
⇒ Efficiency of LED is given by

$$\text{efficiency} = \frac{\text{lumen generated}}{\text{Applied electric power}}$$



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The cutt of voltage is nearly equal to 1.5 which is greater than the ordinary diode



* Advantages of LED:
- It has smaller size and light weight
- Low working voltage (1 or 2 volt)
- Current (5 to 20 mA)
- Very fast response time (≈ 10 ns)
- Long life
- High reliability

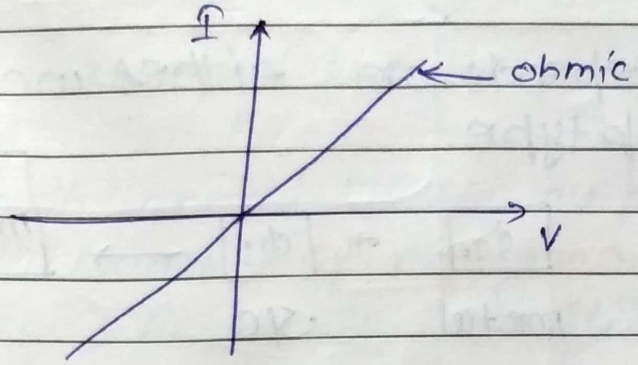
* Uses:
- As display devices
- In optical communication system.

* Metal s/c Junction:
are those J^n which are formed b/w a metal and s/c
these are of two types
(1) Rectifying Contact: also called Schottky diode or schottky barrier device/ Recti°

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2) Non Rectifying Contact / ohmic Constact
- It is formed by heavely doped of s/c
- in contact region

- metal s/c J^n refers to a contact which allows a current to flow in one Direction and block in other dir^n like Normal diode



(1) Schottky diode or Schottky barrier diode:
It work on the Principle of Scottky effect
" when the negative charges are brought near a metal surface the two charges induced in the metal It causes Introduction of Charge forces when metal is subjected to an electric field the charge forces Combine with it and reduce the effective work function ($e\phi_f$) to some extent Such reduction in work function is known as Scottky effect.

this mech^n can be explained by two specific Cases
(i) when s/c is of n type
(ii) " " " " p type.

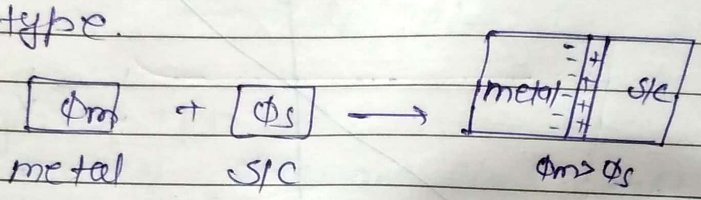
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- When ϕ_{sc} is n type:

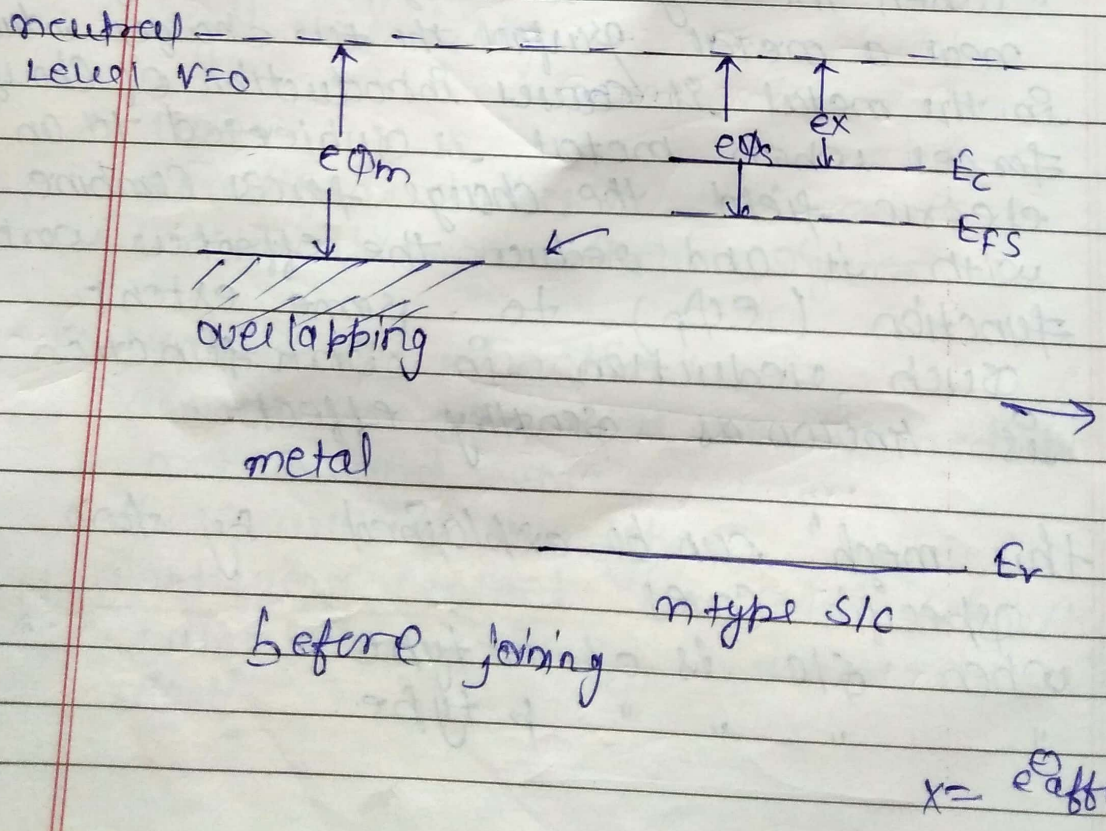
$e\phi_m$ ⇒ work fn of metal
$e\phi_{sc}$ = " " " ϕ_{sc}
E_{fm} = fermi level of metal
E_{FS} = " " " ϕ_{sc}

for n type $\phi_m > \phi_s$

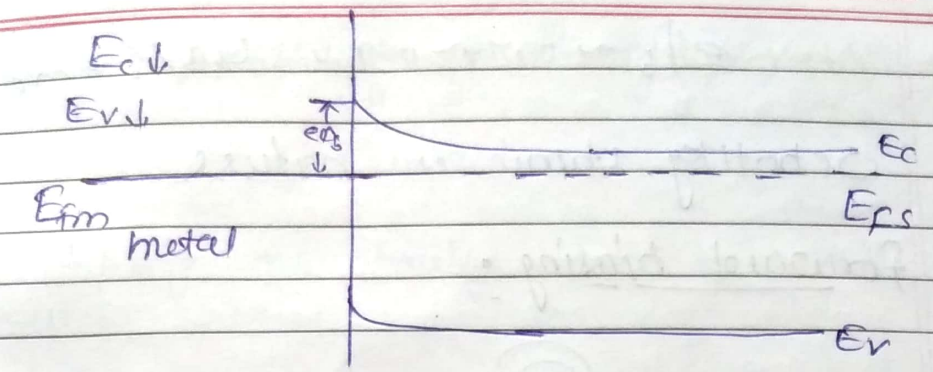
ϕ_s depends on either we use n type or p type.



Imp: Energy band diagram of Schottky diode



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After joining

$e\Phi_b$ = schottky barrier or schottky potential

When both metal & s/c are brought in contact transfer of charge take place as $E_{fs} > E_{fm}$ so, to align Fermi level at same level at eqb $e^{\ominus}$ potential of s/c has to be raised as $e^{\ominus}$ energy must be lowered w.r.t the metal at eqb diffusion of electron from C.B to metal is stop due to potential known as schottky potential and barrier

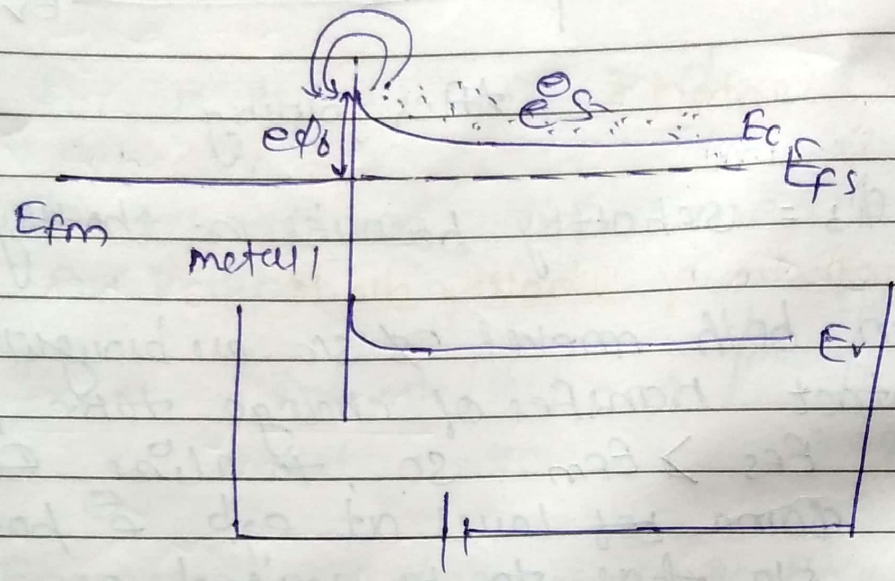
and its value is given by $e\Phi_b = e[\Phi_m - \chi]$

In general $\chi < \Phi_m$

$e\phi_b \approx 0.7 \sim 0.9$ V · GaAs + metal

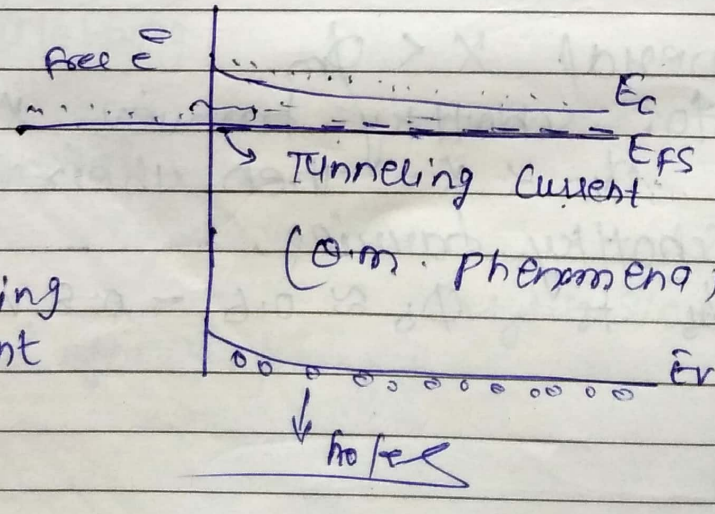
Schottky ohmic in nature

forward biasing:



- Current is produced due to thermionic emmition
- I_f = thermonic ~~effect~~ emmi emission current
- as energy is good up $e^\ominus$ moves across the barrier and produce thermonic emission

R.B



RR = Tunneling current

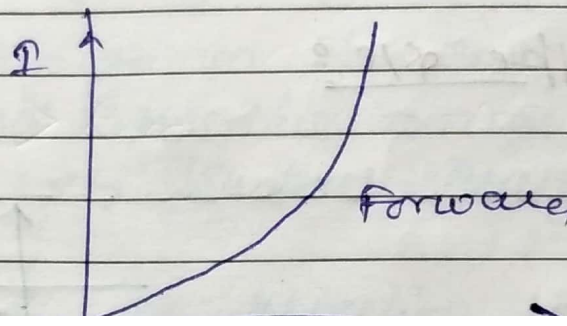
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tunneling probability is directly proportional to $\frac{1}{\text{width of barrier}}$

by doping o/c barrier width can be reduced ~~level~~

* Ohmic Contact :
ohmic contact means resistive i.e $I \propto V$

* Characteristic of Schottky diode :



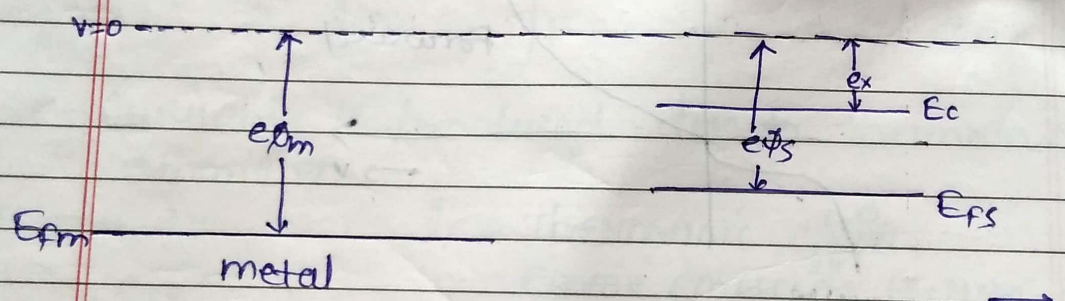
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In ohmic V-I characteristics the scale on I and V axis should be same

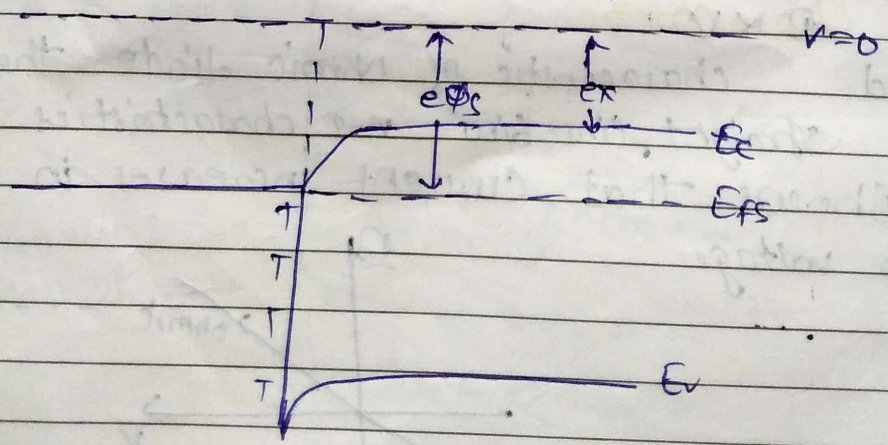
- Mech^n of ohmic contact can be explain by two process
(i) For N type S/C
(ii) P type S/C

N type S/C	P type S/C
$\phi_m < \phi_s$	$\phi_m > \phi_s$

(i) For N type S/C :



n type SC



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- Ohmic Contact can not be obtain practically so to get nearly ohmic contact we use n type s/c of highly doped

- Ef aligns at eq^b by transfering $\ominus e$ from metal to s/c

- So Potential drop across s/c is given by

$$\text{Potential drop} = e(\phi_s - \phi_m)$$

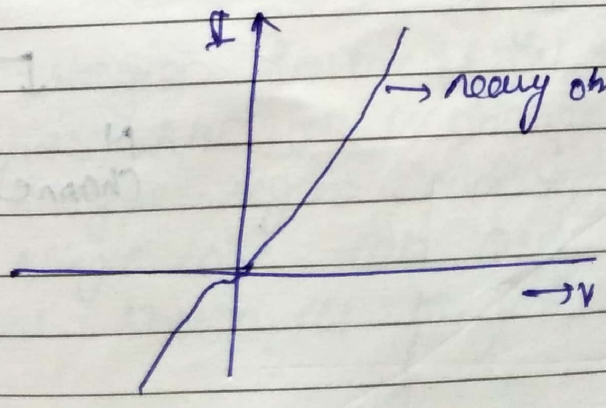
- Negative charge in s/c surface is surface charge and positive charge in metal charge is also surface charge.

- So there is no depletion layer or region in s/c

- So, Barrier to flow $\ominus e$ from metal to s/c or s/c to metal is small.

- It shows non rectifying action or ohmic Contact.

* VI characteristic of nearly ohmic Contact



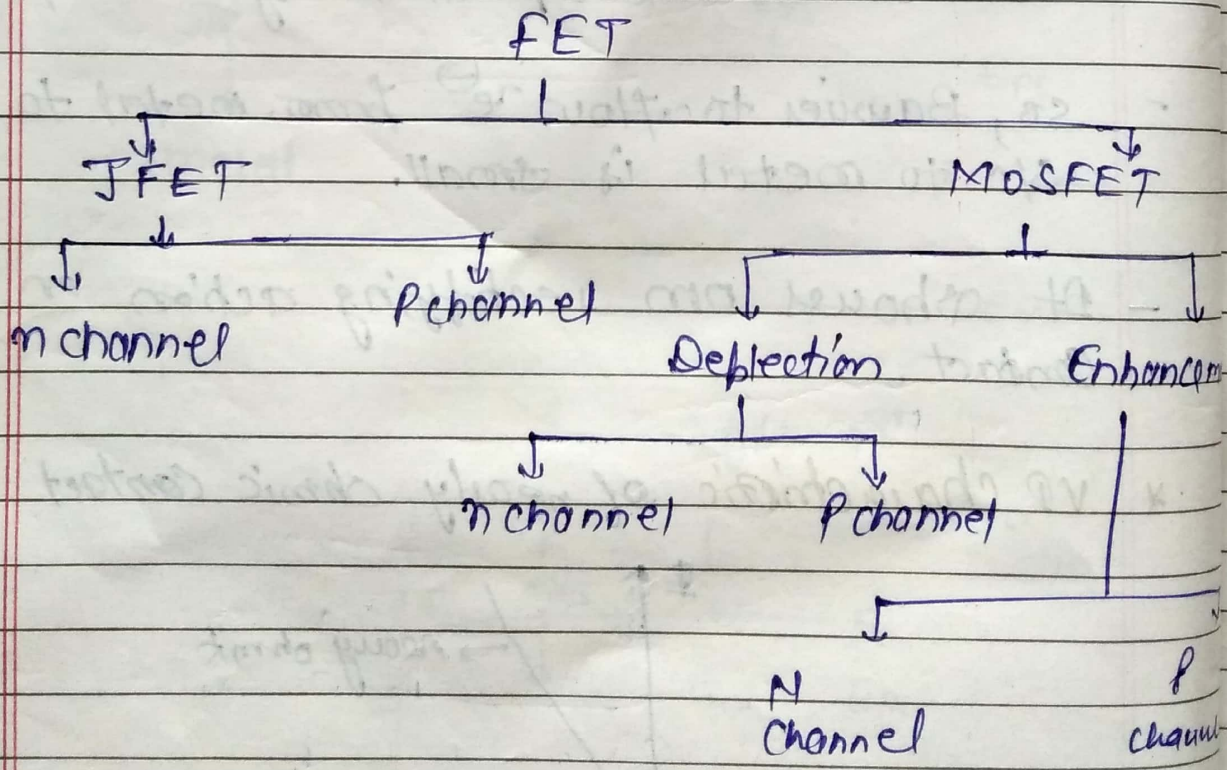
* Field Effect Transistor : (FET) :

A FET is a three terminal device in which current conduct by one type of carrier either by $e^{\ominus}$ or holes.

And is controled by Effect of Electric field

- It is another type of transistor which is Voltage controled unipolar device. O/P characteristic of FET are controlled by applied I/P voltage

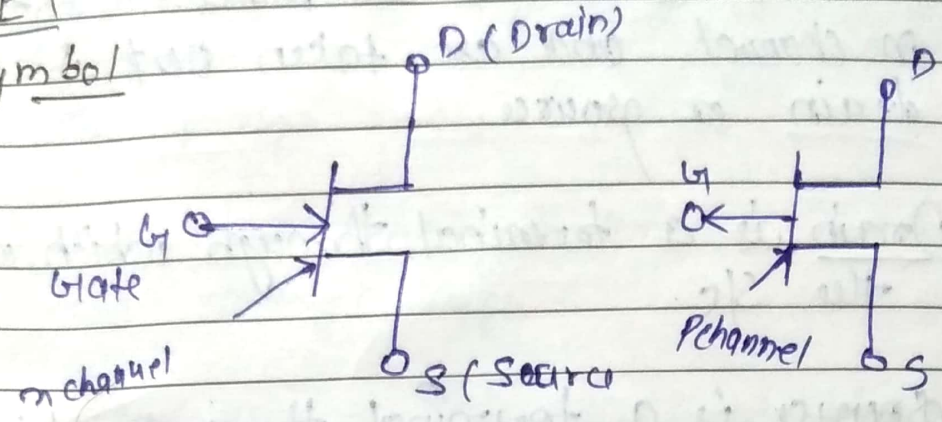
- There are two types of FET
(i) Junction field effect transistor (JFET)
(ii) metal oxide s/c field effect transistor (MOSFET)



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JFET

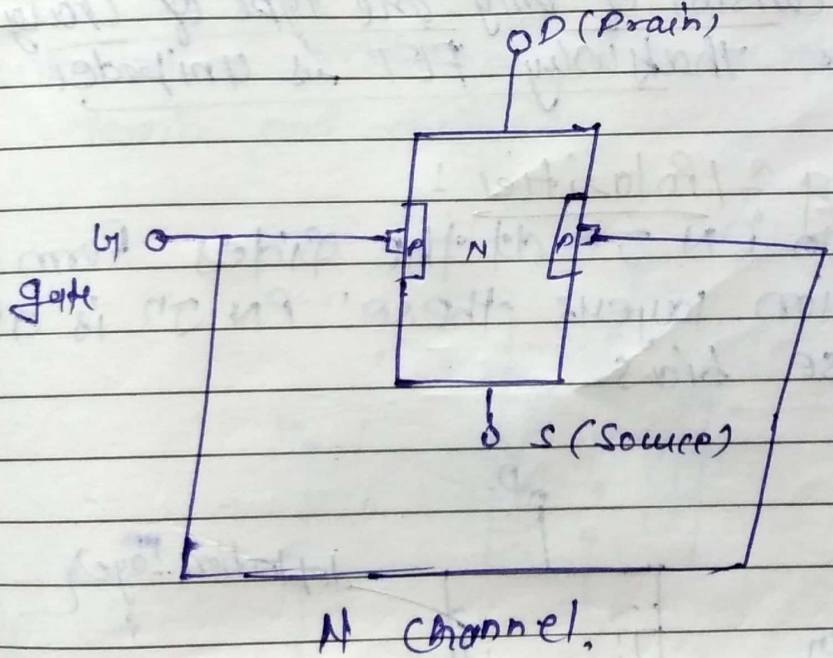
Symbol



N channel P-channel

The construction

On n channel JFET and n type s/c bar which two P type s/c havily doped region diffuse on opposite side of middle path



N channel.

- P type region formed the two PN Jn
- the space b/w JR is known as channel bothe P type region connected internally and a single wire take out in form of terminal known as Gate.

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Electrical connection are made to both ends of n channel and are taken out in form of drain or source.

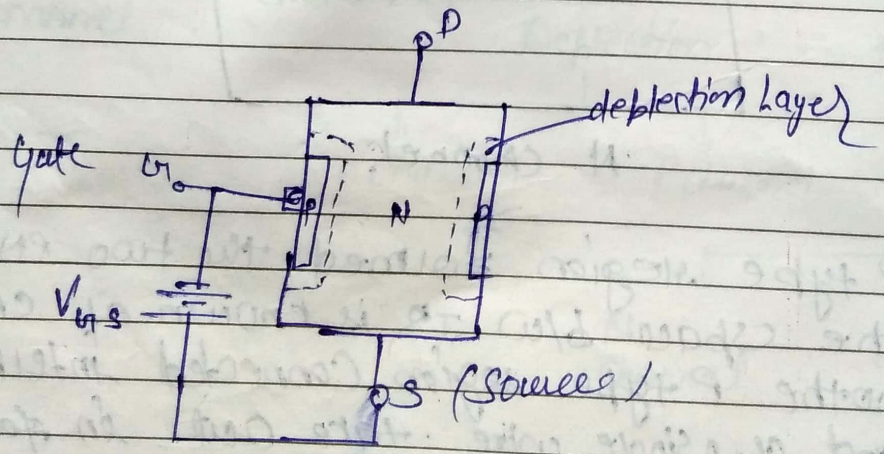
⇒ Drain is a terminal through which $e^{\ominus}$ leave the s/c

⇒ Source is a terminal through which $e^{\ominus}$ enter the s/c

when ever a voltage is applied b/w drain and source a current flow through n channel

⇒ Current consist of only one type of charge carriers thatswhy FET is unipolar

* Working / Polarities :
The two PN Jn of the sides form two depletion layers these PN Jn is always reverse bias



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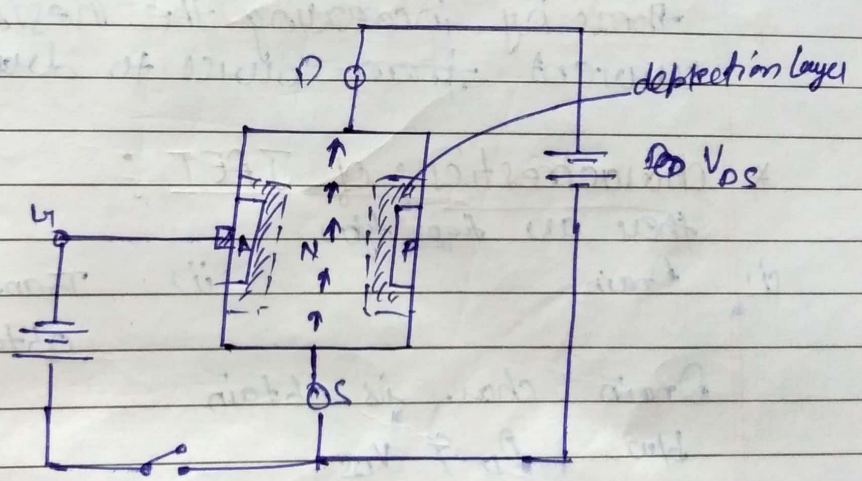
The current conduction by charge carriers through channel b/w two depletion layer and out of the drain

The width and hence Resistance can be controlled by the voltage V_{GS}

Greater the V_{GS} wider the depletion layer and more the conducting channel which reduce the source to Drain current

Note: The JFET operates on the principle that width of Conducting channel can be varied by changing the value of V_{GS}

When a voltage V_{DS} is applied b/w drain and source

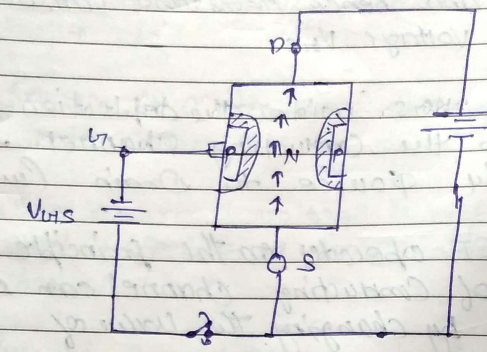


① and $V_{GS} = 0$
the two PN jn at the gate established depletion layer and size of this layer determine the width of Channel

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through which current is conducting

(2) when V_{DS} is applied and V_{GS} reverse bias



V_{GS} ↑ width ↓ Conduction Reduce

the width of depletion layer increased which reduce the width of channel thereby increasing the Resistance. I_D, current from source to drain ↓es.

* Characteristics of JFET :

there are two types

(i) Drain (ii) Transfer

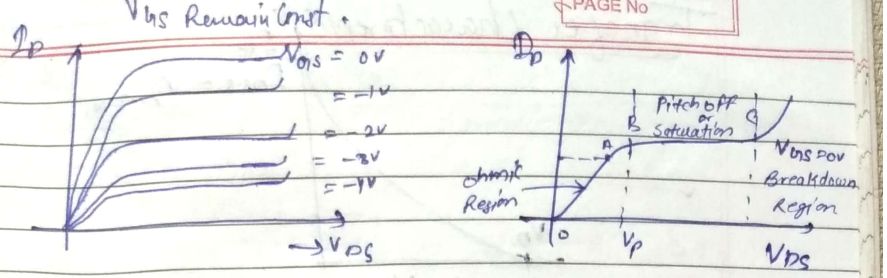
Drain char. is obtain b/w I_D & V_{DS}

obtain b/w I_D & V_{GS}

Drain Char.



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- In ohmic region of drain current ↑es linearly with the voltage and obeys the ohms Law this is due to the fact n S/C ↓ as a simple Resistor Behave

- Curve AB

I_D is varies with V_{DS} but Not linearly it is due to the ~~breath~~ of depletion Layer and reducing width ~~length~~ of channel

- Saturation Region / Pitch off :
Current Remain Constant or independent to the V_{DS} and its max. value is I_{DSS}

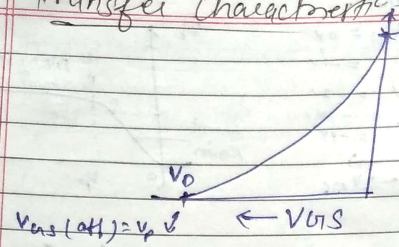
$$I_D = I_{DSS}\left[1 - \frac{V_{GS}}{V_p}\right]^2$$ Schottky eq.

V_{DSS} ⇒ max. Drain Current

* Breakdown Region :
In BDR I_D increase
It is due to the Breakdown of gate to source Jn due to avalanche effect

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Transfer characteristics



It is the curve b/w I_D and V_{GS} for Const. value of V_{DS}

* JFET Parameters:

(i) D.c drain Resistance (R_{DS}) :

$$R_{DS} = \frac{V_{DS}}{I_D}$$

(ii) AC drain Resistance (r_d) :

$$r_d = \frac{\Delta V_{DS}}{\Delta I_D}$$

This is the Output Resistance

* Trans Conductance

It is also known as forward transe Conductance or ~~forward~~ transmittance. It is given as the ratio of small change in drain current to change in V_{GS} for Constant V_{DS}

$$g_m = \frac{\Delta I_{DS}}{\Delta V_{GS}} \quad \text{for const. } V_{DS}$$

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* Amplification factor (μ):
It is the ratio of small change in V_{DS} to small change in V_{GS}

$$\mu = \frac{\Delta V_{DS}}{\Delta V_{GS}} = \frac{\Delta V_{DS}}{\Delta I_D} = \frac{\Delta I_D}{\Delta V_{GS}}$$

$$\mu = r_d \times g_m$$

* Input Resistance (R_i):

$$R_i = \frac{V_{GS}}{I_{GS}}$$

* Advantages of JFET:
It has very high input impedence which permits high degree of insulation b/w input and output circuits. It has the negative temp. cofficien Resistance which avoids the risk of thermal run away
- It has small size, longer life and high efficiency.
- high Power gain
- Produces the less noise

* Disadvantages:
- It can not be used as Current amplifier
- Voltage gain of JFET amplifier is less then Transistor Amplifier

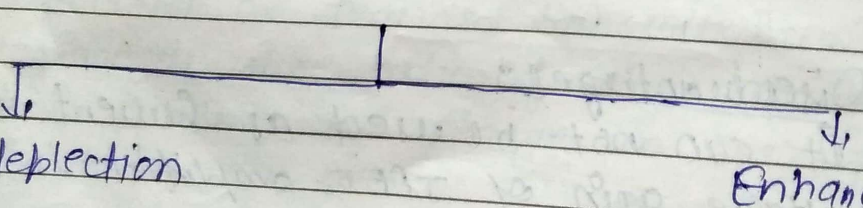
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* Difference b/w JFET and transistor :-

- JFET is a voltage controlled device as Current I_D is controlled by applied voltage b/w gate and source
- Transistor is current controll device as the output current I_C is controlled by varing the base current.
- JFET is current flow through only due to one type of charge carriers either holes and $e^{\ominus}$
- Transistor has a Bipolar device in which current flow by both holes and $e^{\ominus}$

* MOSFET :- (Metal oxide sc field effect transistor)

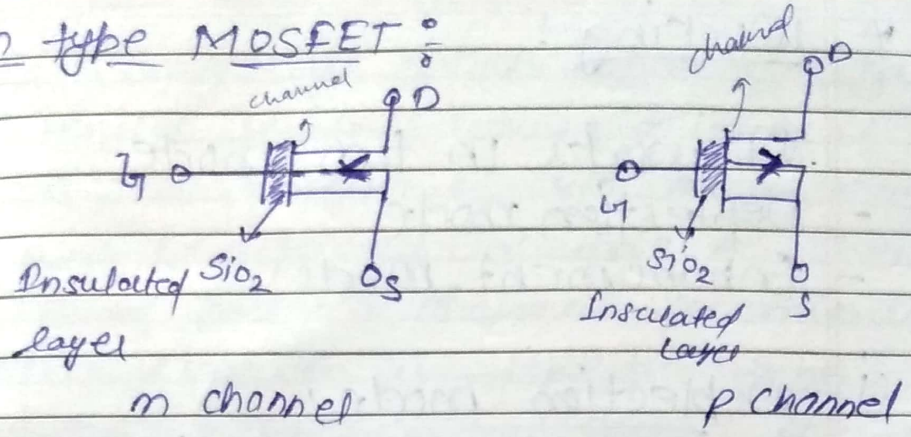
Like JFET MOSFET has a source gate and drain however unlike JFET gate of MOSFET is insulated from the channel due to this MOSFET is also known as IGFET (Insulated Gate field effect transister)



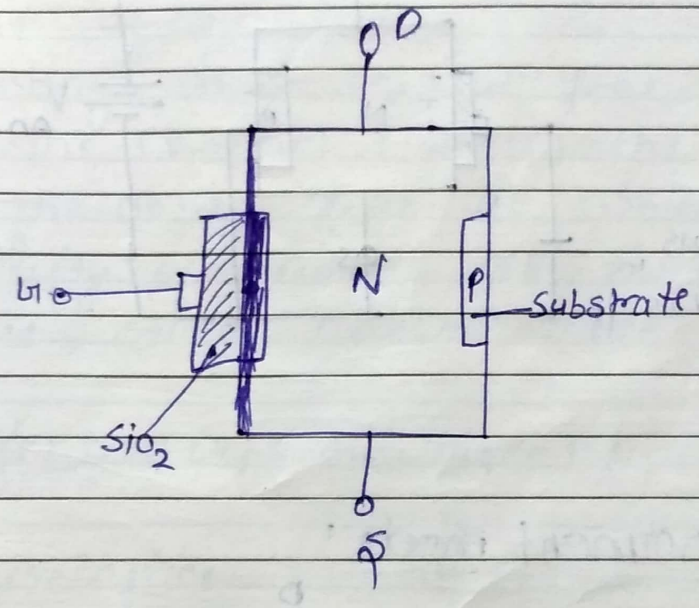
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(1) * Depletion type MOSFET :

(1) Symbol



(2) Construction :



N channel depletion type MOSFET consist of a Conducting bar of N type material with an insulating gate on left and P region on right.

~~with an insulting material~~ P from source to drain through So P region is called substrate.

- the thin Layer of SiO_2 insulate Gate from channel in negligible current flow in gate terminal.

Drain

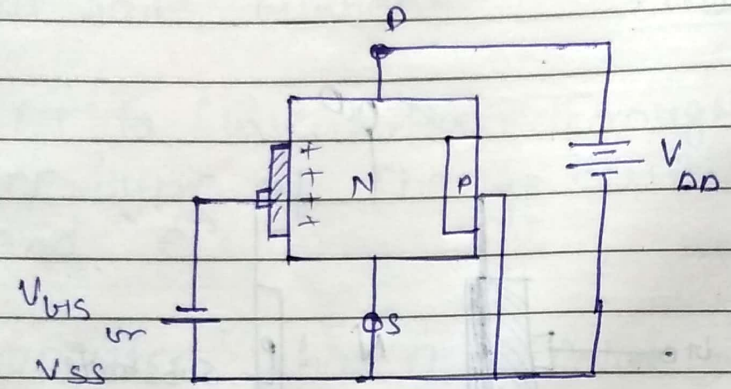
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* Working :

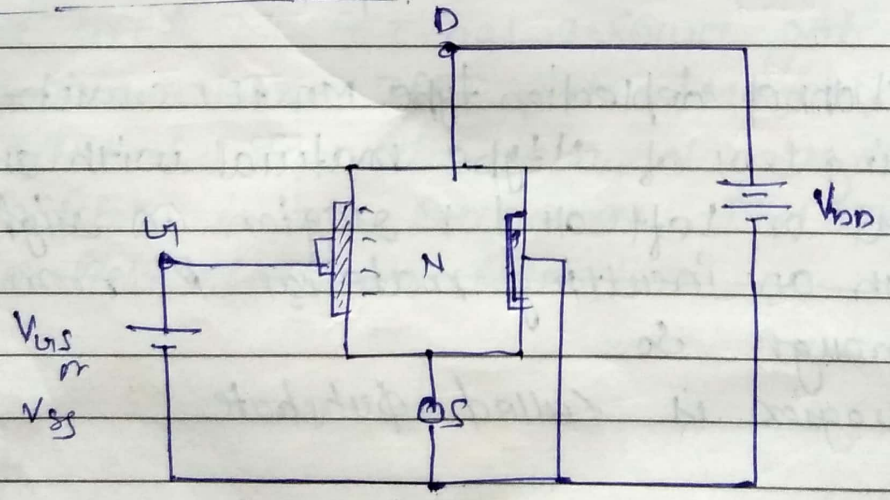
It works in two mode
- Deplection mode
- Enhancement mode

(i) Deplection mode :

In DM Gate voltage is negative



(ii) Enhancement mode :



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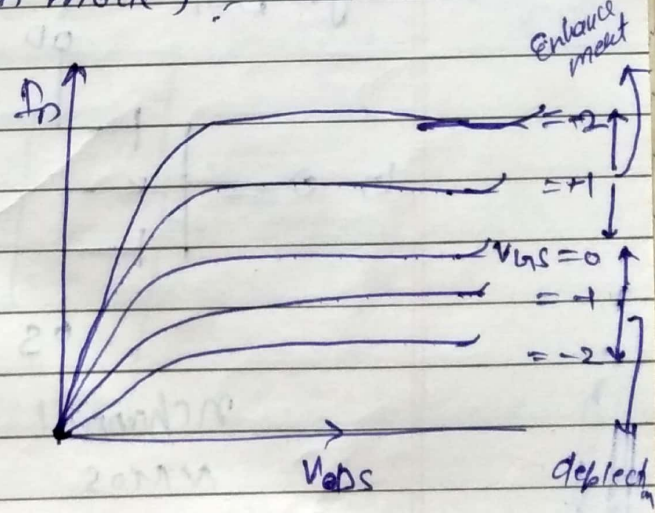
DM

In DM Gate is negative which repel the free $e^{\ominus}$ in n channel leaving a layer of +ve ion on the surface of SiO_2 as a result n channel will be depleted of free $e^{\ominus}$. therefore less no. of free $e^{\ominus}$ available for conduction Relatively this is known as depletion type. Depletion type MOSFET conduct even if $V_{GS} = 0$ bcz of this is commonly known as ON MOSFET

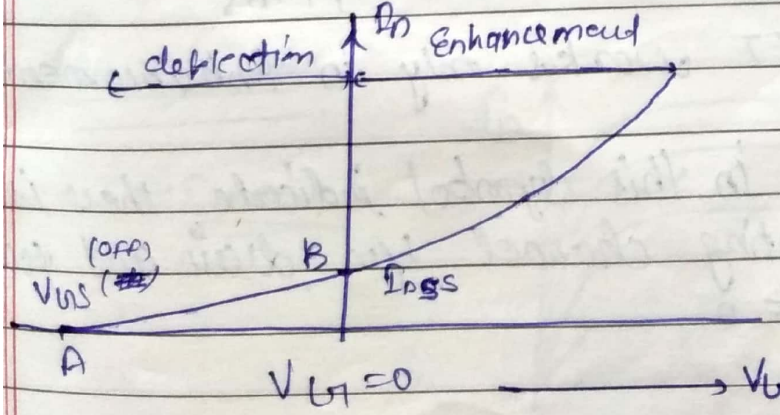
Enhancement type:
+ve Gate voltage increase the free $e^{\ominus}$ passing through the channel greater the voltage greater the no. of free $e^{\ominus}$ which enhance the conductivity of channel ϕ, Positive Gate operation is called enhance mode.

Characteristics: (Depletion mode):

Drain characteristics



Transfer



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- the AB region of transfer characteristic is similar to JFET the difference is that this curve is extents towards the +ve side of V_{GS} also

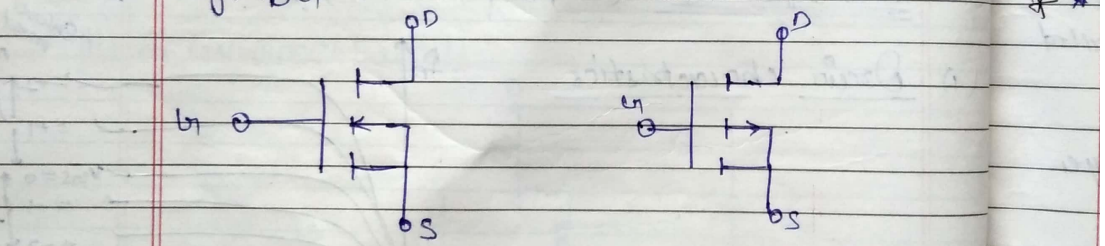
- when $V_{GS}=0$
  then I_{DSS} represent the drain current where drain current is given by

$$I_D = I_{DSS}\left[1 - \frac{V_{GS}}{V_{GS(off)}}\right]^2$$

when $V_{GS} = 0$, $I_D = I_{DSS}$ and in this condition it is known as on MOSFET

(2) Enhancement type MOSFET:

(1) Symbol



n channel
NMOS

P channel
PMOS

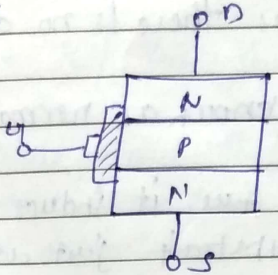
this MOSFET works only in Enhancement mode.
Broken line in this symbol indicate there is no conducting channel b/w drain and source at $V_{GS} = 0$

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This device is also known as Normal of MOSFET

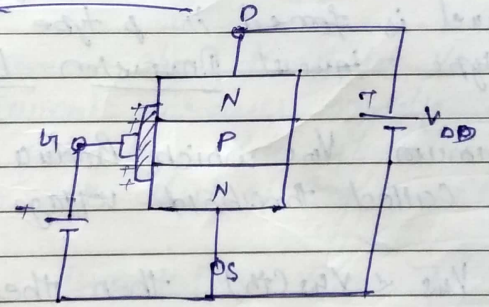
N-channel Enhancement MOSFET also known as NMOS
" " " " " " " PMOS

Constractions:



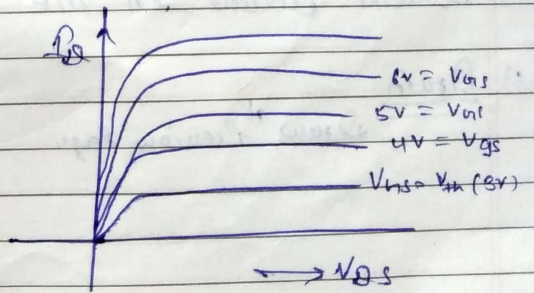
The constraction is same as depletion type MOSFET the main difference is there is no physical channel b/w drain and source.

Working / Polarities:



Characteristics:

① Drain



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Working

- always operate with +ve V_{GS}
- when $V_{GS} = 0$ V_{DD} supply tries to force free $e^{\ominus}$ from source to drain But Presence of P Region does does not permit $e^{\ominus}$ to pass through it thus there is no drain current when $V_{GS} = 0$

Thereby it is known as normally off MOSFET

- when V_{GS} = +ve it induce Negative Charges in p type substrait just adjesent to SiO_2 layer.
- when Gate is +ve enough it can create a no. of free $e^{\ominus}$. This form a thin layer of electrons which stretches from Source to drain due to this a thin layer of n type channel is formed in p type substrate called N type Inversion Layer.
- minimum V_{GS} which Produce inversion layer is called threshold voltage $V_{GS(th)}$
- If $V_{GS} < V_{GS(th)}$ then there is no current when $V_{GS} > V_{GS(th)}$ a Significant current Produce in the device.

(1) Drain

Draw at Previous Page

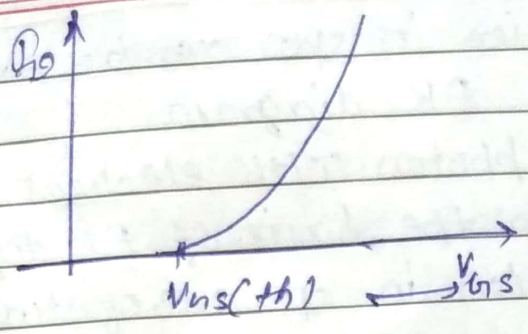
(2)

Unit-4

- S/C for Optical
- For Probe method

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(2) Transfer



$$I_D = K\left[V_{GS} - V_{GS(th)}\right]^2$$

- Drain curve shows that when $V_{GS} < V_{GS(th)}$ there is no drain current But Practically a very small drain current flow through it due to Reverse of thermal generated $e^{\ominus}$ in P substraight.

- When $V_{GS} > V_{GS(th)}$ then I_D can flow

⇒ Transfer char.

If V_{GS} increase above threshold V_{GS} then drain current increases rapidly and its value is given by this eq^{n} when k is Const depends on data sheet of ~~Cons~~ MOSFET

$$I_D = k\left[V_{GS} - V_{GS(th)}\right]^2$$

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Unit - 4

Optical Transition in semiconductor :

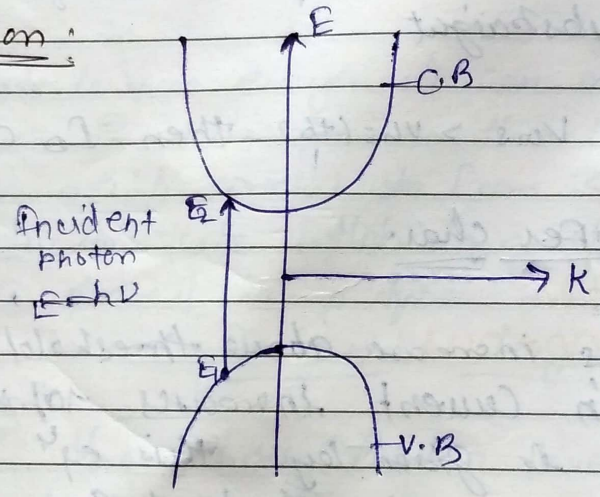
- Optical transition in s/c can be explain with the help of EK diagram
- Interaction of photon with electrons in s/c can be explain on the basis of EK digram.
- optical transition in s/c are of two types

1. Absorption
2. Emission

Emission is again of two type

(1) Spontaneous
(2) stimulated

(1) Absorption :



$E_2 - E_1 = h\nu$

E_1 = Energy state of $\ominus$ in V.B

E_2 = " " " " " C.B

When a photon of energy $h\nu$ is incident on a s/c then this photon is absorved by an $\ominus$ in V.B and electrons moves to Energy state E_2 in C.B

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In absorption Generation of $e^{\ominus}$ and hole pair take place

- Absorption is the basis of photo detections. In photo detector we generally have a reverse bias diode. when an photon is incident on this junction when generation of $e^{\ominus}$ and hole pair takes place so photo current generate due to the incident photon

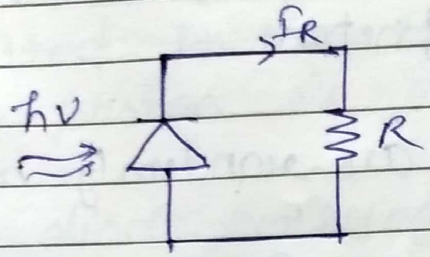
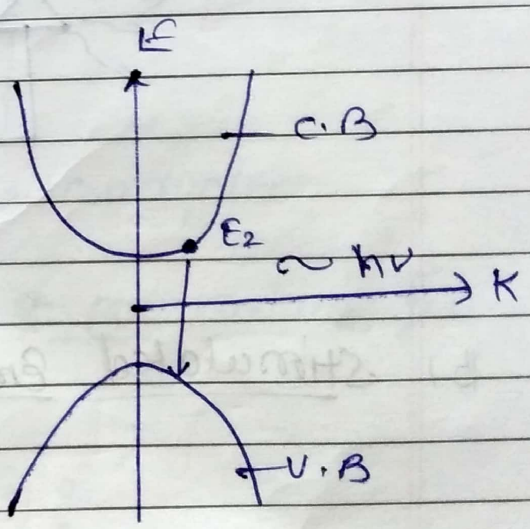


Photo detector

(2) Emission:

(a) spontaneous:



$E_2 - E_1 = h\nu$

E_1 = Energy state of e in VB

E_2 = " " " " " C.B

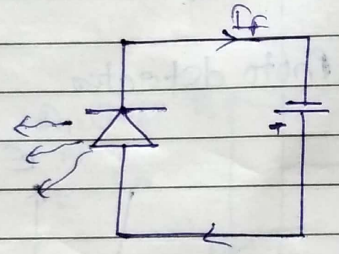
In Spontaneous Emission $e^{\ominus}$ from E_2 state of C.B Jumps to the E_1 state of V.B without any external help emitting a photon of energy $h\nu$

$h\nu = E_2 - E_1$

Spontaneous emission is the basis of operation of LED.

On LED, a forward bias current I_f is flow in the junction and due to this it gives out light in form of photon in this e-hole pair recombination produce the photon

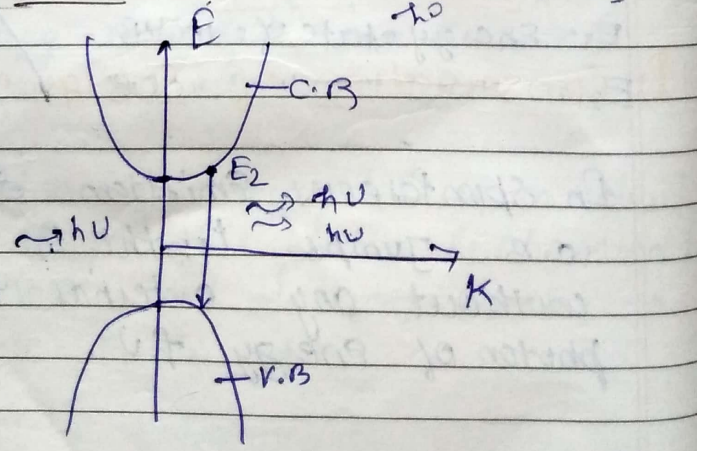
these photon are randomly moving in diff. dir.



LED

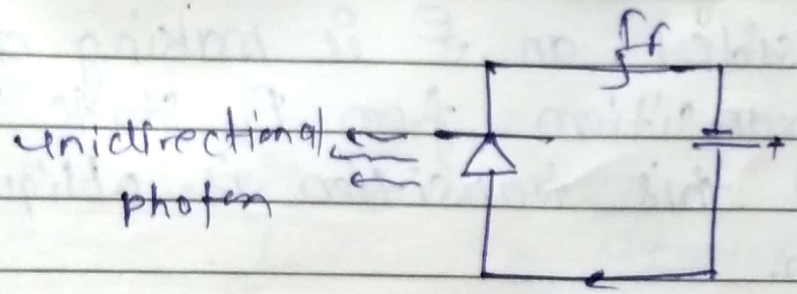
(b) Stimulated Emission:

trigger and stimulate



of laser s/c. In this when a forward current If is passes through the junction the emitted photon which are dipicted as coherent photon i.e in phase.

In Laser diode emission is unidirectional



* Conservation of Energy & momentum in optical transition:

1) Conservation of Energy:
Energy is conserved when a photon is either incident or emitted in a direct band gap s/c during

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- During incident of photon absorption takes place which is given by

$$h\nu = E_2 - E_1$$

- When photon is released the emission take place it may be spontaneous or stimulated and emission is given by

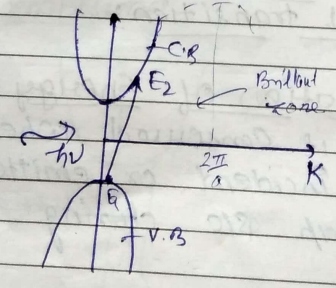
$$E_2 - E_1 = h\nu$$

- In both Process absorption or emission energy is conserved

2. Conservation of momentum:

Let us consider, an $e^{\ominus}$ is making an upward transition from E_1 state to E_2 state and this transition is oblique transition.

momentum before absorption should be equal to momentum after absorption



$P = \hbar K$

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$\hbar K_{photon} + \hbar K_1 = \hbar K_2$

$\hbar (K_{photon} + K_1) = \hbar K_2$

$$\boxed{K_{photon} + K_1 = K_2} \quad - (A)$$

$\lambda \approx 1 \mu m$

$K_{photon} = \frac{2\pi}{\lambda}$ $\quad \lambda \rightarrow$ wavelength of light

$K_1 = \frac{2\pi}{\lambda_{1e}}$ $\quad \lambda_{1e} \rightarrow$ de Broglie wavelength of $\ominus$ in V.B.

$K_2 = \frac{2\pi}{\lambda_{2e}}$ $\quad \lambda_{2e} \rightarrow$ " " " "
" $e^{\ominus}$ in C.B

$\lambda_e \approx 10 - 100 \text{ Å}$

- $\frac{2\pi}{L} \leq \lambda_e \leq \frac{2\pi}{a}$ ← Interatomic distance.

↑ s/c size or length

As wave length of electron is much larger than the wavelength of photon

$K_{photon} \ll K_e$

$K_1 = K_2$

or $\boxed{\Delta K = 0}$

Acc. to Conservation of momentum the allowed transition in EK digram is only vertical transition and when a photon is intract with a $\ominus$.

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* Non Radiative or Radiative transition:

(i) Radiative transition:
RT are transitions which involves emission or absorption of a photon.

Ex: transition b/w direct band gap s/c

(ii) Non-Radiative transition:
does not envolve emission or absorption of a photon.

Ex: transition b/w Indirect band gap s/c

In this emittion of phonon takes place which have very small energy and momentum. So, in Indirect band gap s/c the presence of phonons can not be neglected.

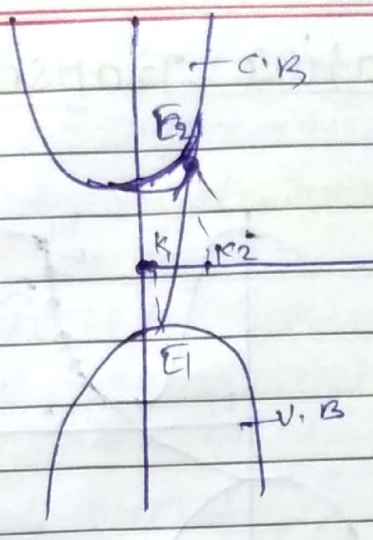
In this phonon emission Predominent over the photon emission.

* Radiative Transition in Case of oblique Transition:
as for momentum conservation the allowed ~~Tan~~ Transition is $\Delta K = 0$ which is vertical. Transition but in actual practice $\Delta K \neq 0$

$= K_1 - K_2$

has finite value. In Case of oblique Transition.

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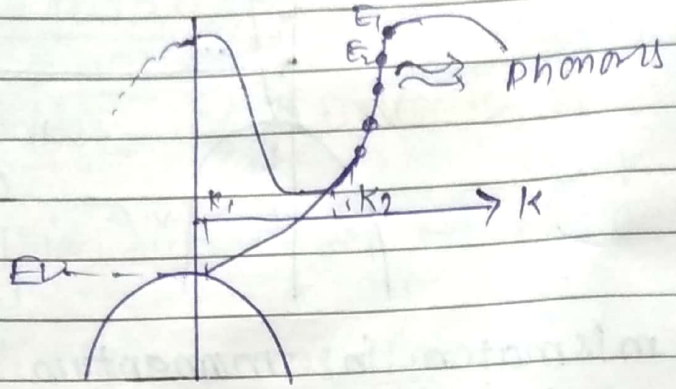
compensate by phonon

The mismatch in momentum as $\vec{K}$ is compensate of we consider these are phonon which also take part in this radiation as this Transition Take place with help of phonons. This is known as phonon asisted radioactive Transition but as energy difference Eg in case of Si is 1 or 1.5 ev so, the energy conservation during oblique Transitions is taken care by photons as phonons have very small energy whereas in momentum Conservation phonon particle take place.

The Probability of occuance of phonon asisted radiative transition is much lower than the vertical transition. so, in this case vertical Transition plo dominant over the phonon asested radiative Transition. Indirect Band gap. Si/C $e^{\ominus}$ holes. & phonons takes ~~pats~~ part in radiative.

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* non-radiative Transition in indirect bandgap sc:



(1) As $E_1 - E_2$ is very small
or $E_2 - E_3$ is very small
so, Energy released by $e^{\ominus}$ in the form of phonons
as phonon is low energy particle

So, E Conservation taken care by phonons
In energy Conservation $e^{\ominus}$ moves in C.B from Higher to lower Energy State by process of thermalization

(2) as $K_1 \neq K_2$ & ΔK has a finite value which is given by consideration of phonons

In momentum Conservation as phonons have K value which is comparable with K_1 & K_2 of $e^{\ominus}$ thus in this case phonon momentum not neglected
In this case radiations by the

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phonons which has very small energy So, It is no radiative Transition. In this, photons do not Take place.

x What is phonons :-
In a crystal atoms are bound by elastic Bond which are in state of vibration due to finite thermal e. the atoms which vibrate or Late in nature has some e associated with then a quanta of these lattice vibrations are phonons

Phonons are of two types.
① Acoustic phonons
② optical phonons

(1) acoustic phonons :-
(i) In acoustic . If one atom is displaced in one direction & another adjacent atom displaced in opp direction then this type of vibration is known as acoustic phonons type of vibration is known as acoustic phonons

(ii) The magnitude of both the atom can be different in opposite direction.

(iii) The wavelength of acoustic phonon is higher.

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(2) optical phonon :
A group in atom move in upward direction whereas the adjacent whereas the adjacent group of atoms moves in downward direction then this type of vibration is known as optical vibration

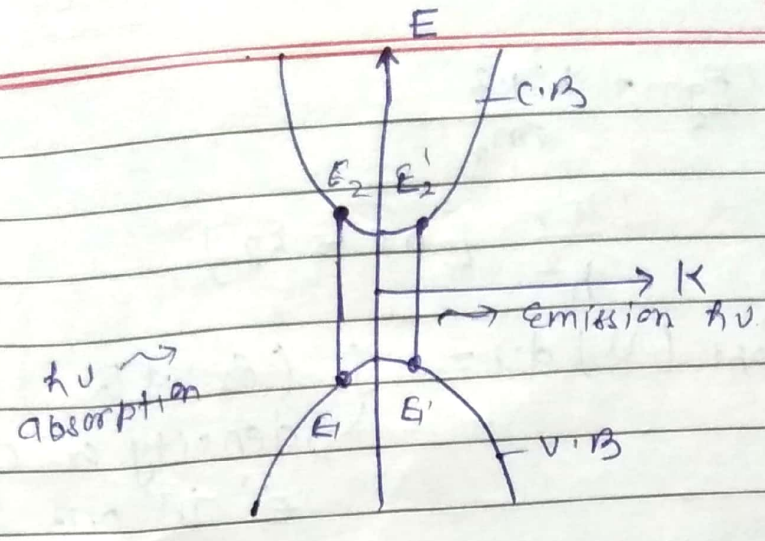
wavelength of optical phonon is lower then the acoustic phonon.

optical Joint density of state :
It is generally denoted by (J_{opt}). It is the member of state available for photos to interact with simultaneous. It for photos to interact with simutanious. it take care of state in V.B & C.B

In optical Transition joint density of state is Important. where as in Electron process. we always deal with C.B & V.B separately but a photon interact with SIC Involve a state in VB & a state in CB simultaneously

J_{opt} = no. of state / vol. for photons having energy $h\nu$ & $h(\nu + \delta\nu)$

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E_1 & E_2 energy state of $e^{\ominus}$ in V.B & C.B for absorption

E_1' & E_2' Energy state of $e^{\ominus}$ in V.B & C.B for emission

$$E_2 = E_c + \frac{\hbar^2 k^2}{2m_c}$$

$$E_1 = E_v - \frac{\hbar^2 k^2}{2m_v}$$

$$E_2 - E_1 = (E_c - E_v) + \frac{\hbar^2 k^2}{2}\left[\frac{1}{m_c} + \frac{1}{m_v}\right]$$

$$E_2 - E_1 = (E_c - E_v) + \frac{\hbar^2 k^2}{2m_r}$$

$$\boxed{\frac{1}{m_r} = \frac{1}{m_c} + \frac{1}{m_v}}$$

$$E_2 - E_1 = E_g + \frac{\hbar^2 k^2}{2m_r}$$

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$$h\nu = E_g + \frac{\hbar^2 k^2}{2m_r}$$

$$k^2 = \frac{2m_r}{\hbar^2}\left[h\nu - E_g\right]$$

as $f_{opt}(\nu)\,d\nu = f_c(E_2)\,dE_2$

↳ density or conc^n of $e^{\ominus}$ in C.B

as $$f_c(E_2) = \frac{1}{2\pi^2}\left(\frac{2m_c}{\hbar^2}\right)^{3/2}(E_2 - E_c)^{1/2}$$

& for dE_2 use eq^4 (A)

$$E_2 = E_c + \frac{\hbar^2 k^2}{2m_c}$$

$$k^2 = \frac{2m_r}{\hbar^2}\left[h\nu - E_g\right]$$

$$E_2 = E_c + \frac{\hbar^2}{2m_c}\cdot\frac{2m_r}{\hbar^2}\left[h\nu - E_g\right]$$

$$E_2 = E_c + \left(\frac{m_r}{m_c}\right)(h\nu - E_g)$$

$$\frac{dE_2}{d\nu} = \frac{m_r h}{m_c}$$

$$f_{opt}(\nu) = \frac{1}{2\pi^2}\left(\frac{2m_c}{\hbar^2}\right)^{3/2}(E_2 - E_1)^{1/2}\frac{m_r}{m_c}$$

$$= \frac{1}{\pi\hbar^2}(2m_r)^{3/2}(E_2 - E_c)^{1/2}\frac{m_r}{m_c}$$

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$$= \frac{1}{\pi\hbar^2}(2m_c)^{3/2}\left(\frac{m_r}{m_c}\right)^{1/2}(\hbar\nu - E_g)^{1/2}\frac{m_r}{m_c}$$

$$\boxed{J_{opt}(\nu) = \frac{1}{\pi\hbar^2}(2m_r)^{3/2}(\hbar\nu - E_g)^{1/2}}$$

It is the final optical Joint density of state which tells us about how many energy space are available for phonon for Transition.

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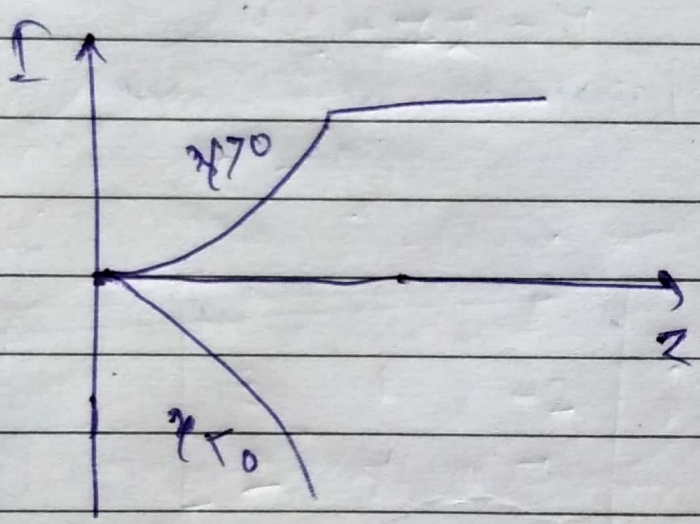
* Absorption spectrum / loss coefficient of absorption :

$$I_{r(out)} = I_{r(in)} e^{\gamma z}$$ $z \rightarrow$ length of s.c material

γ = gain constant / coefficient

$\gamma > 0$ there is amplification

$\gamma < 0$ there is Attenuation



$$\gamma = \frac{v^2}{8\pi v^2} \frac{1}{\tau_r} (2m_r)^{3/2} \frac{1}{\pi\hbar^2} (h\nu - E_g)^{1/2}$$

* If $f_g(\nu)$ is negative ($f_g(\nu) < 0$)

γ = -ve &

$$\boxed{f_{out} = f_{in} e^{-\gamma z}}$$

$$\gamma = \frac{-\nu^2}{8\pi\nu^2} \frac{1}{\tau_r} (2m_r)^{3/2} \frac{1}{\pi\hbar^2} (h\nu - E_g)^{1/2} f_o(\nu)$$

$$\because f_o(\nu) = |f_g(\nu)|$$

$$\gamma = -\alpha_a$$

α_a = attenuation constant / coefficient

$$\alpha_a = \frac{\nu^2}{8\pi\nu^2} \frac{1}{\tau_r} (2m_r)^{3/2} \frac{1}{\pi\hbar^2} (h\nu - E_g)^{1/2} f_o(\nu)$$

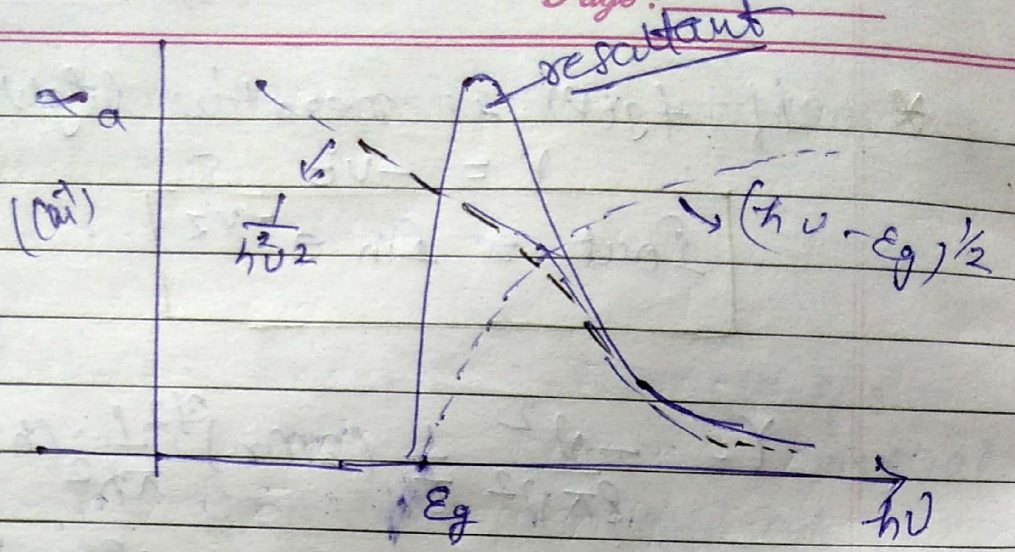
$$v = \frac{c}{n}$$

where n = refractive index of material

$$\alpha_a = \frac{(c/n)^2}{8\pi\nu^2} \cdot \frac{1}{\tau_r} (2m_r)^{3/2} \frac{1}{\pi\hbar^2} (h\nu - E_g)^{1/2} f_o(\nu)$$

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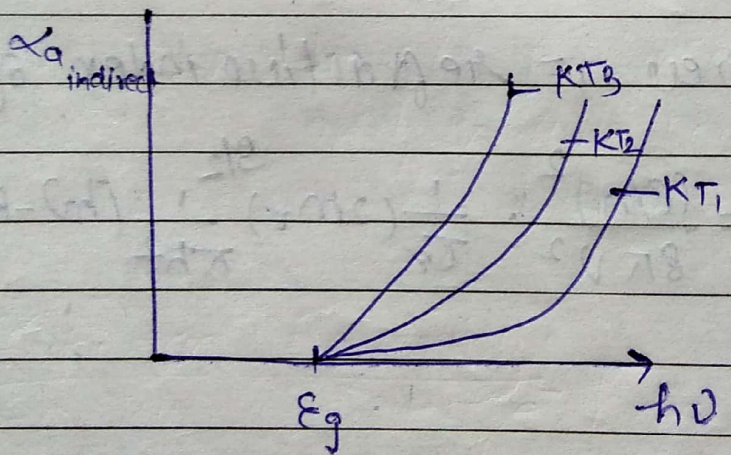


- this Graphs shows the variation of α_a only for direct band gap s/c

- the α_a for indirect band gap s/c is given by

$$\alpha_a \approx [K_0 + K_1(\text{temp})][h\upsilon - \varepsilon_g]^2$$

where K_0 and K_1 is Constant dependent T.



$T_3 > T_2 > T_1$

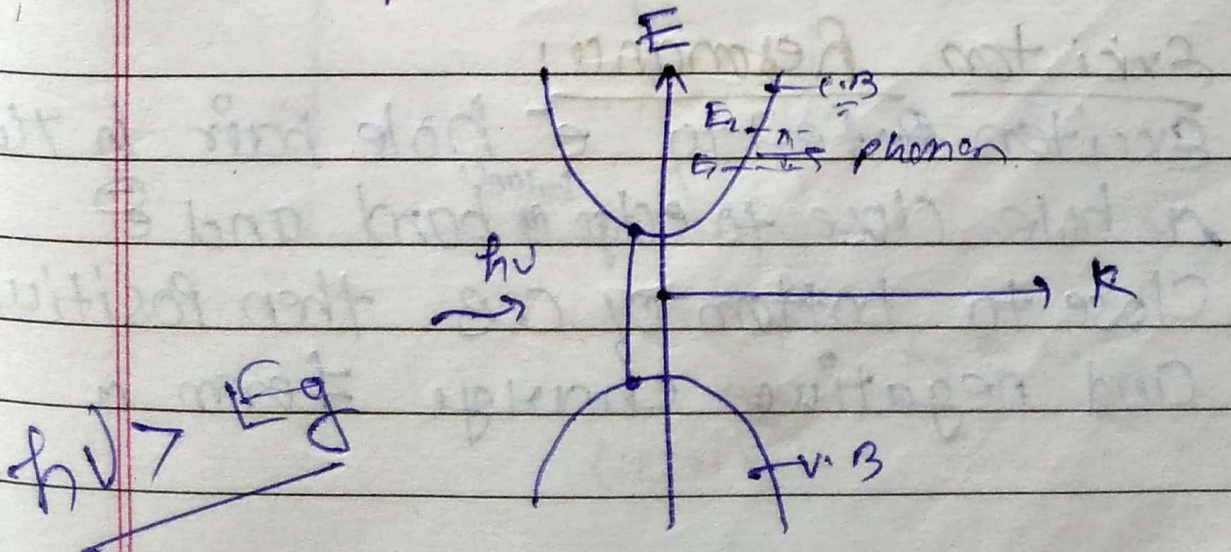
* Types of Transition in absorption Process of s/c :

There are four type of transition Possible

(i) Inter band transition [C.B → V.B & V.B → C.B]

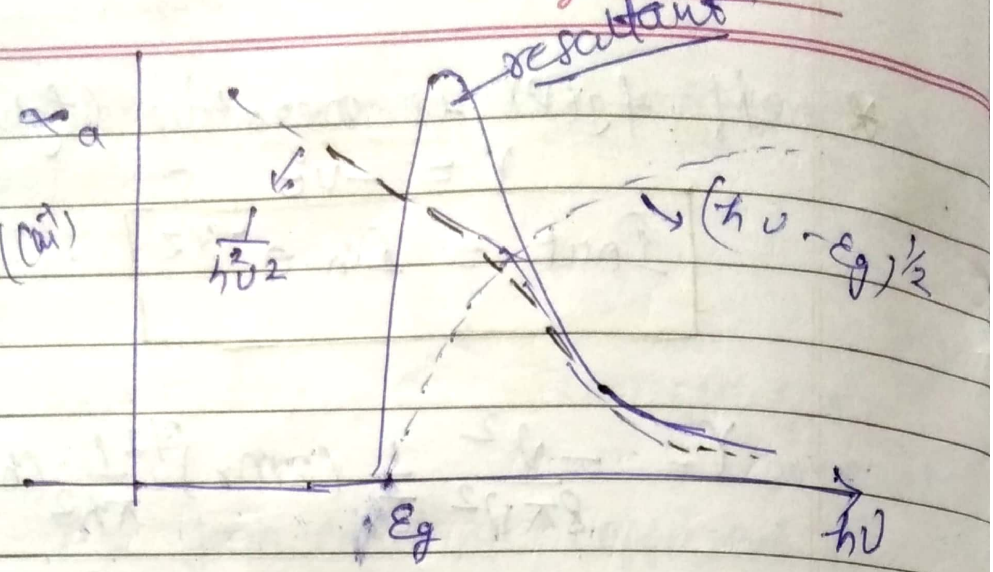
(ii) Intra band " [from inside the same band either in C.B & V.B]

In this Low energy or Low freq. transition take place.



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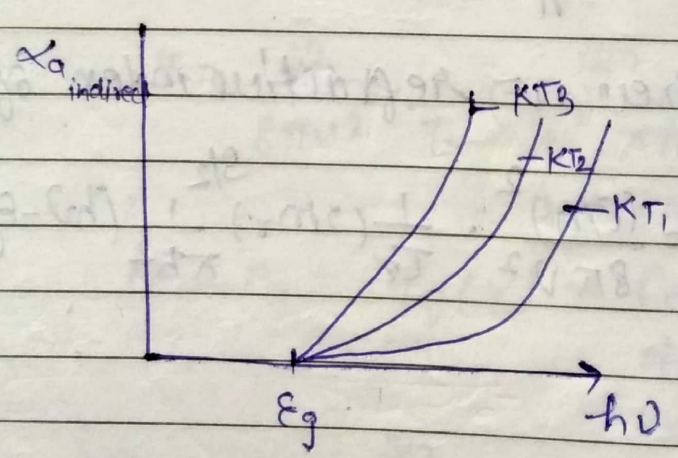
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- This Graphs shows the variation of α_a only for direct band gap s/c
- the α_a for indirect band gap s/c is given by

$$\alpha_a \approx [K_0 + K_1 (temp)][h\upsilon - E_g)^2$$

where K_0 and K_1 is Constant dependent T.



$T_3 > T_2 > T_1$

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So the net absorption =

= radiative absorption + non radiative absorption

- The probability of radiative absorption is very high in direct band gap S/C where as in indirect band S/C probability is very low (because of phonon assisted transition or violation of momentum conservation).

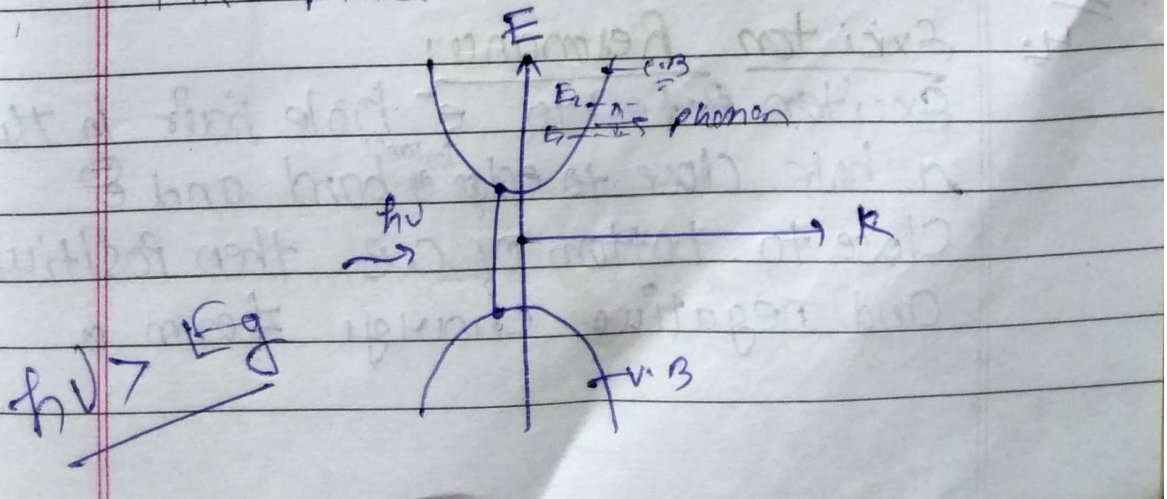
* Types of Transition in absorption Process of S/C :

There are four type of transition possible

i) Inter band transition [C.B → V.B & V.B → C.B]

(ii) Intra band " [from inside the same band either in C.B & V.B]

In this low energy or low freq. transition take place.



position (state) is known as hot ē. these hot ē subsequently comes down due to thermilization.

3. Phonon transition :

when ē in C.B at higher energy state comes to the lower energy state it release energy in terms of phonon energy which has very small value

$$E \approx 0.01 \text{ ev} - 0.1 \text{ ev}$$

this transition is known as phonon transition and in this low energy photons generated the phonons

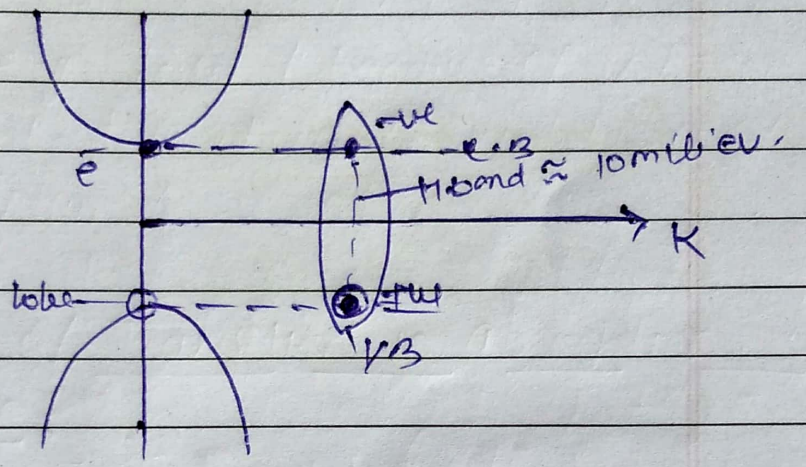
Coloumb

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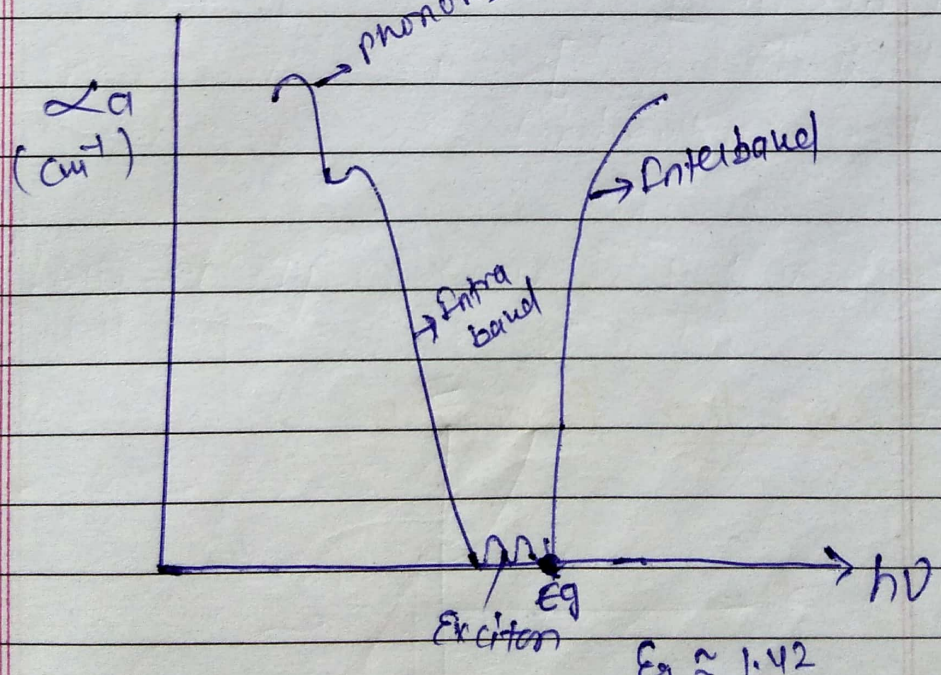
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Hydrogen bond due to quatimic Coloumbic attraction. so $\overset{\ominus}{e}$ and hole are localised this localised entity called exciton

Binding energy of exciton is nearly equal to 10 milli ev.



* Complete Spectrum of absorption in g/c:



GaAs.

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Unit - 5

Heterojunction & associated band diagram

On the basis of structure P-N Jn can be divided into three categories

Homojunction:
The jn b/w same type of semiconducting material.
ex: n or p types of Si.
the the jn is called homojunction

Schottky Jn:
the jn b/w semiconducting material and metal

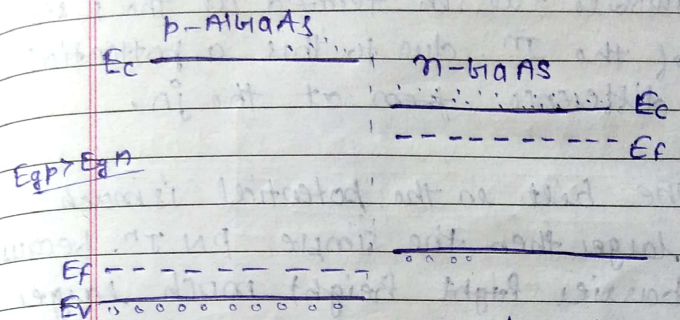
Heterojunction:
the jn b/w two dissimilar material usually diff. band gap.
It can be P N Jn, P-P Jn and N N Jn.
when two semiconducting material have the same type of conductivity then it is known as isotype hetro jn

when the conductivity of two semiconducting material are diff. such as P N Junc. then it is called an isotropic hetro jn.

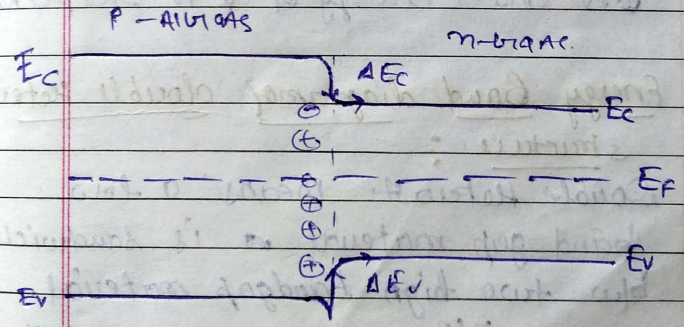
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Energy band diagram of hetro junction :

1. Single heterostructure / Junction.



before the junction.



After the jn.

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Conc^n of electrons are higher in n type n-GaAS where as Conc^n of holes are higher in P-AlGaAs . So, diffusion take place and a mobile immobile -ve ion formed at the P side of the J^n. due to this a pottential difference ~~from~~ at the jn.

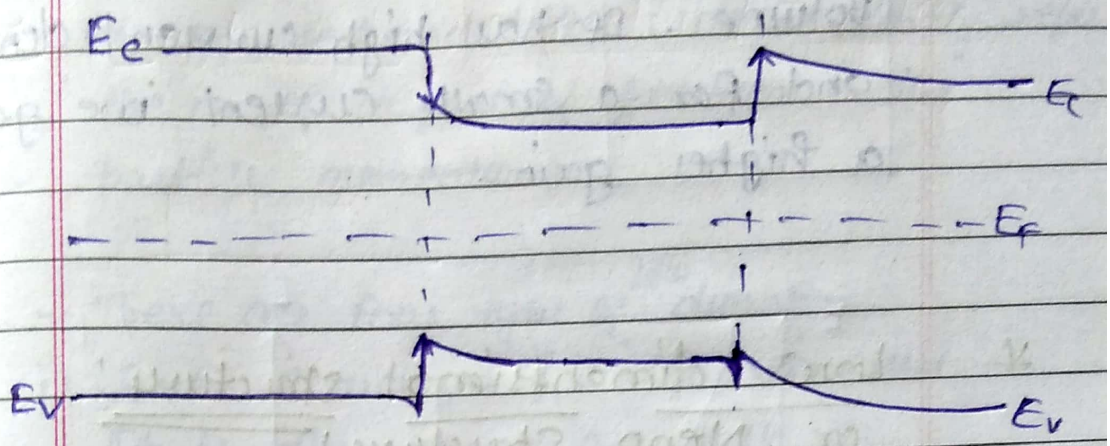
The bilt in the potential is much larger then the simple PN J^n. because barrier ~~fright~~ height much larger

ΔE_c & ΔE_v are known as the differencing known as energy of C.B and energy of V.B respectively

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$n_p > {}^{p+}n_p{}^{p} > n_p{}^{n}$



After J"

In Double Heterostructure the intermediate layer has a potential well under non bias condition. or we can say that a large no. of $\bar{e}$ and holes Presence in Intermediate region and $\bar{e}$ and hole recombine due to this a current flow in external circuit.

- The width of diplection region in case of Heterostructure is 1 μm which can be controlled. but in case of P-N Junction width of PN jn depends depletion region depends on doping level which is not well controlled

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- In Heterostructure for the same current we have large no. of carries in small volume. It has high current density and for a small current we get a higher gain.

* Low dimensional structure or Nano Structure:

When the one or more dimensions of a solid reduce significantly (below 100 nm) its physcochemical characteristic changes. (magnetic Properties changes, chemical Properties, electrical, machenical Properties changes) Resulting new structure low dimensional structure or nano structure

- Nanostructure can be explain with the help of quantum mechanics
- In nano st atleast one dim. in the range of nanometer.

* Classificati
Low dim.
no. of ele
the no. of
particle

- There are
(i) 3-D st
It is al

(ii) 2-D str
(quantu

(iii) 1-D st
(quantu

(iv) Zero di
quant

1. 3D (Th
No quan
occur i
holes i
in all 3

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* Classification of Low dimenssional st. :
Low dim. st. are usually classified acc. to no. of reduced dim. (dimenssionaly refer the no. of degree of freedom in the particle momentum).

- There are four type of Low dim st.

(i) 3-D structure / 3-dim. structure.
It is also known as bulk st.

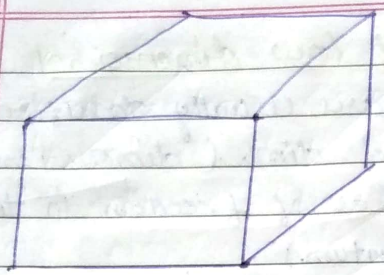
(ii) 2-D structure / 2-dim. structure.
(quantum well.)

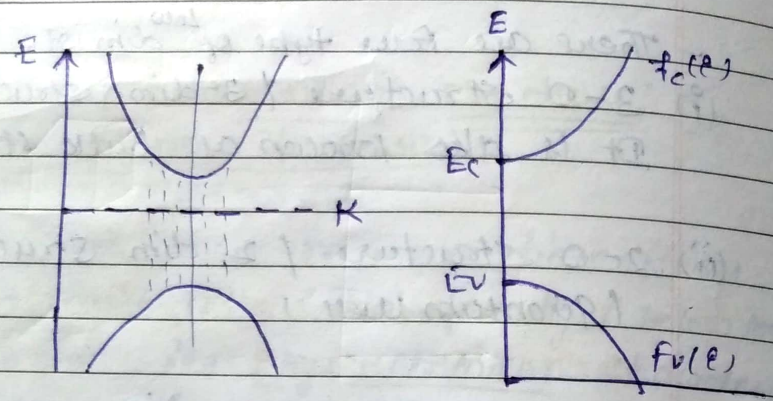
(iii) 1-D structure / 1. dim structure
(quantum wire)

(iv) Zero dim. structure / 0-D st. /
quantum Dot

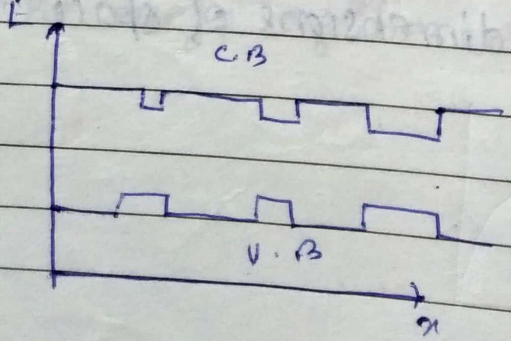
1. 3 D (Three Dimensional) / bulk Structure
No quantization of particle motion occur i.e particle is free. e⁻ in C.B & holes in V.B are free to move in all 3 dimensions of space i.e cube

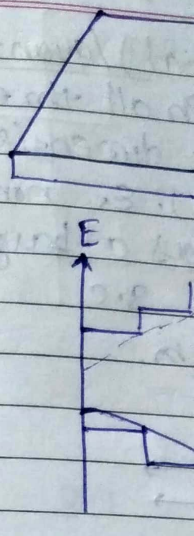
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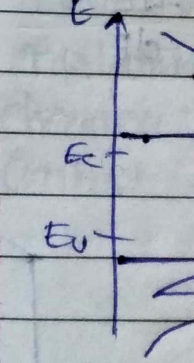


2. 2D (Two dimensional) structure / quantum well:
quantization of particle occurs in one direction, while particle is free to move in the other two directions. (one dimensional is confied or reduced to nm range's while other 2 dim. remain large). Ex. Thin film & quantum well

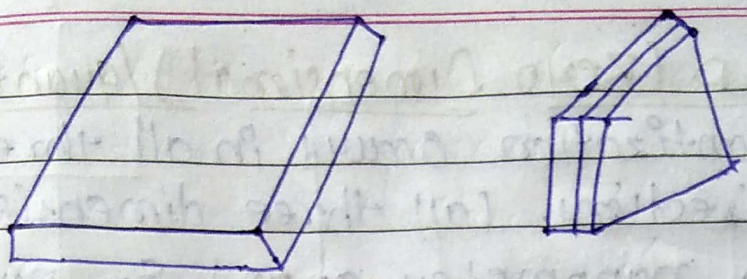


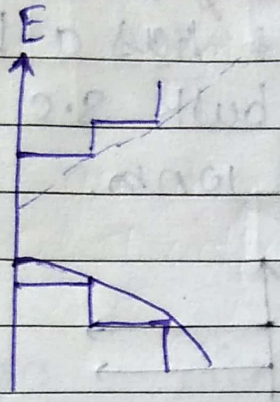


3. 1D (one
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particle
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nano pi

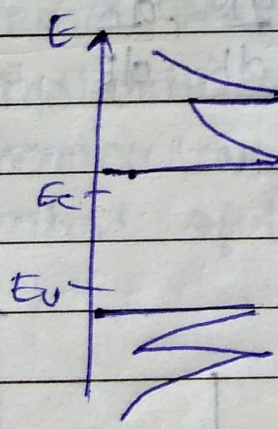


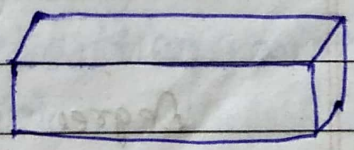
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3. 1D (one dimensional) structure) :/
quantum wire :
quantization occurs in 2 directions, particle is free to move in one direction. (2 dimension are reduced in to nm range & one remain large). Ex quantum wire, ~~named~~ nano pillar

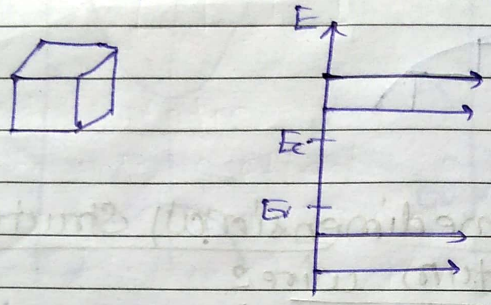




quantum wire

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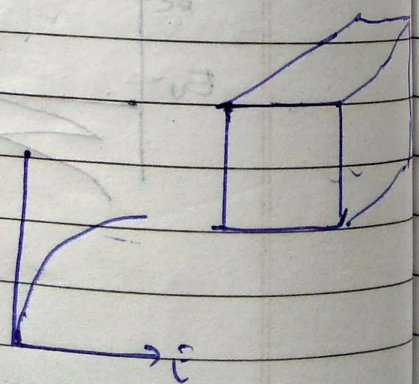
(4) 0D (Zero Dimensional) / quantum dot :
quantization occurs in all three directions. (all three dimension reduced to nanometer range). Ex. nanodot
No quantum dots has a larger band gap like bulk s.c
dimension = 1 - 10nm.



* Density of states (DOS) :
no. of states / interval of Energy of each energy there three available occupied e⊖.

$$DOS = \frac{dN}{dE} = \frac{dN}{dK} \cdot \frac{dK}{dE}$$

St.	Degree of	$\frac{dN}{dE}$
bulk	0D	$E^{1/2}$



Quantum well 1D

Quantum wire 2D

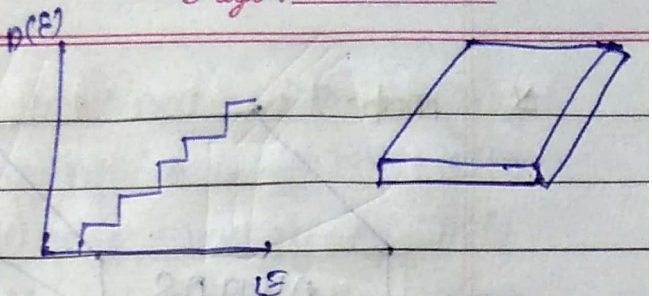
Quantum dot 3D

* Construct
D.O for
material
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i.e Al
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Contrast

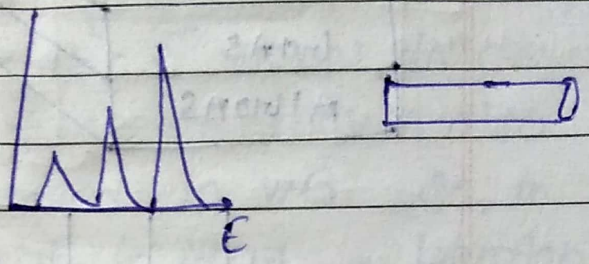
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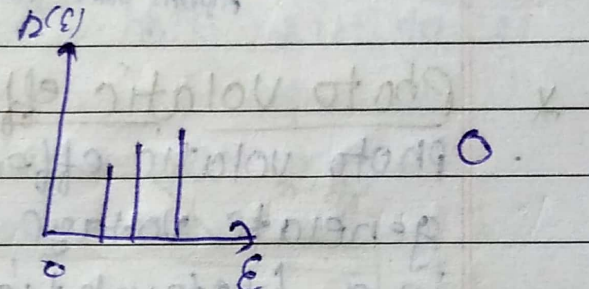
Quantum well — 1D — 1



Quantum wire — 2D — $\frac{1}{\sqrt{E}}$



Quantum dot — 3D — $\delta(E)$



* Construction of quantum well:
  - D.w formed in S.E by having a material like GaAs sandwith b/w 2 large of material with large band gap i.e AlGaAs. i.e Hetero jn structure
  - Ex: Particle in a box.
- These structure can be grown by molecules beam epitaxy or chemical vapour deposition with control of large thickness.

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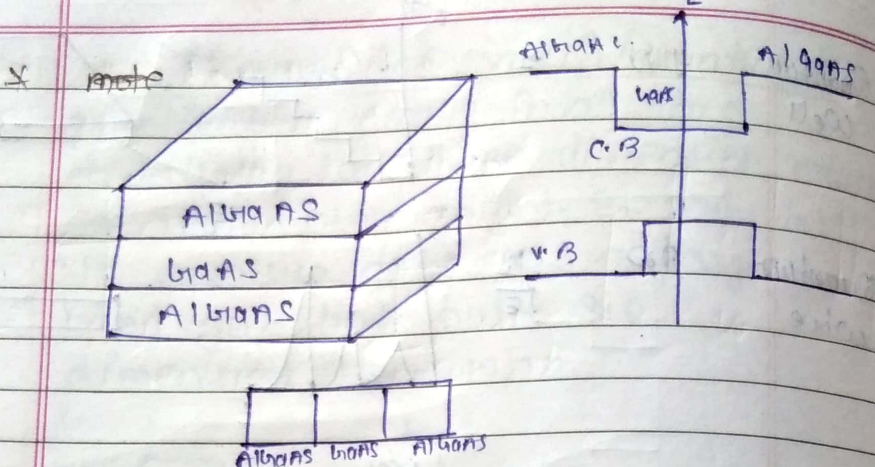
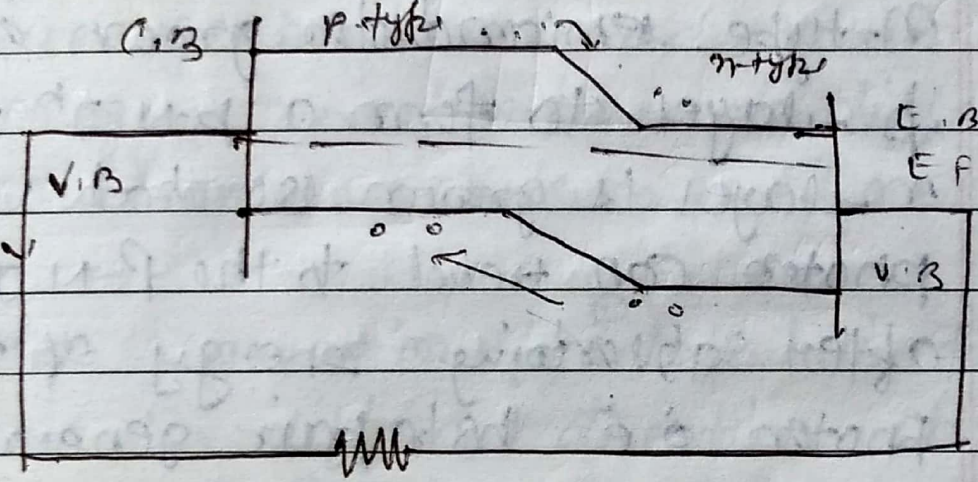


Photo volatic effect:

photo volatic effect is a process that generate voltage or electric current in a photovolatic cell when it is exposed to sunlight. It is this that makes solar panels useful as it is the cells with in the panel convert sunlight to electric energy.

The photovolatic effect occurs in solar cell. These solar cells are composed of two different type of s/c a p-type and a n-type formed together to create a p-N Junction.

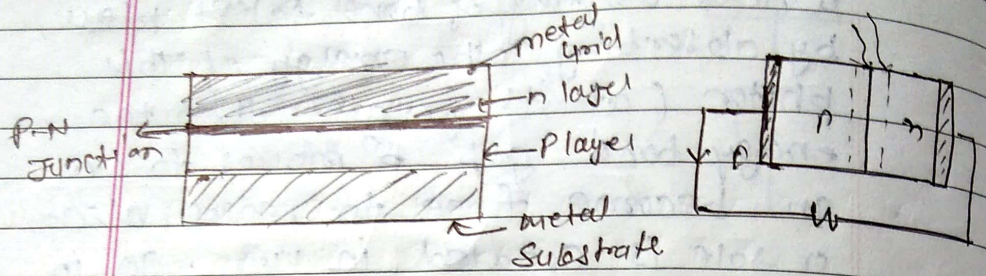
by absorbing the energy of this photon (at its greater then the energy band gap $e^{\ominus}$ moves to C.B an become free to move, also a hole is created in V.B. So, in this way with incident a photon formation of $e^{\ominus}$ hole pair takes place



In a p-N junction electron have the tendency to move down the hill and holes have the tendency to bubble up (up the tall). So in this way, there will be a larger conch of electron one side and hole other side. If we put a change collators both side. and connected through a resister than a current start flowing.

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Construction of a Solar cell



on a metal substrate a p-layer is deposited and a thin layer of n-type semiconductor grown on p-layer to form a P-N Jn. A thin n-layer is grown so that maximum photon can reach to the P-N Jn and after absorbing energy of these photon e⁻ hole pair generation takes place and these charge carriers get called as junctional charge

To form a solar cell a single crystal s/c is used. Efficiency of a single crystal solar cell is about 10-30%

A polycrystalline or amorphous si-semiconductor can also be used to

make s
will ve

- single c
- Poly "
- Amorphou

Efficien
because
spectru
pair g
energy
coarse

→ Also g
more
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make solar cell but the efficiency will very low

- single crystal solar cell 20 - 30%.
- Poly " " " 10 - 15%.
- Amorphous " silicon " 3 - 5%.

Efficiency of solar cell is very low, because all wavelength of solar spectrum not used their $e^{\ominus}$ hole pair generation. and remaining energy, corresponding to different wavelength wasted as that

→ Also generation of $e^{\ominus}$ hole pair they move in different direction change collector, $e^{\ominus}$ holes get recombine again. In poly crystalline solar cell this recombinet is large is compare to single cell this recombination is large is compare to single crystal because any deformity in crystal structure acts as recombination center

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* Lattice matched heterostructure :
If a_s → lattice constant of a structure
a_L → lattice constant of a layer grown epitaxly

- If $a_L = a_s$ then it is known as lattice matched structure. [heterostructure]

if $a_L \neq a_s$ then there will be some atoms which will no participate in bonding and this is called dangling bonds and which work as a defect in the crystal which increase the Non-radiative recombination which decrease the performance of an opto electronic device.

Imp - if $a_s \neq a_L$ even then we can grow the defect free layer when the thickness of growing level is below a critical thickness and this is called Strande layer epitaxly. bez there is a bilt in strain in the layer

* Strained layer exitaxly : If a_s and a_L is not matched this may lead to dangling bands

these atoms
constant. If
quick

- there will be
which compres
and also a
due to this

a_L { a

a_s

$d_L < d_c$

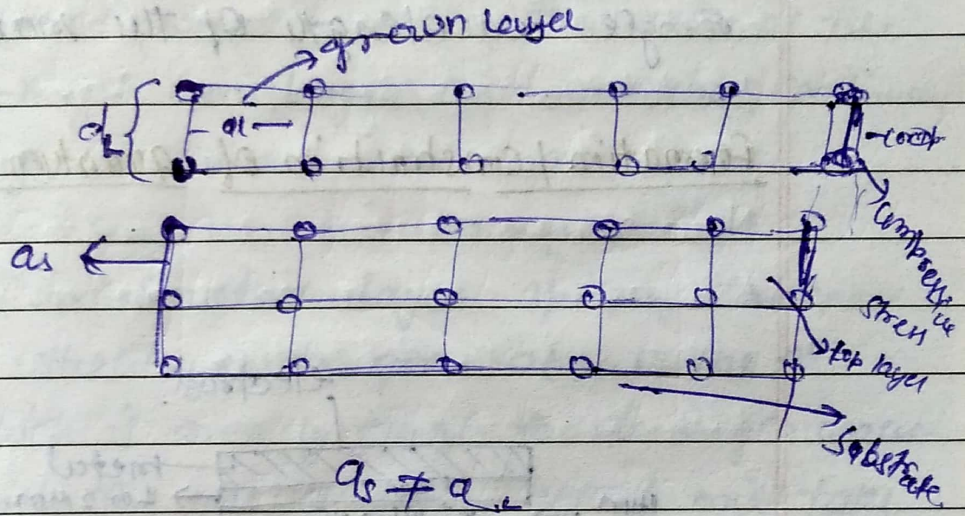
$d_c =$ C / 2

$d_c \Rightarrow$ critical thickness.

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these atoms will adjust their lattice constant. if the layer grown is very thick

- there will be a compressive strain which compress the lattice atoms of layer and also a tensile strain will develops due to this atoms will be elongated.



$a_s \neq a_L$

$d_L < d_c$

$d_c = \frac{a_s}{2|\epsilon|}$

$\epsilon \Rightarrow$ mismatch Parameter

$\epsilon = \frac{a_L - a_s}{a_L}$

$d_c \Rightarrow$ critical thickness.

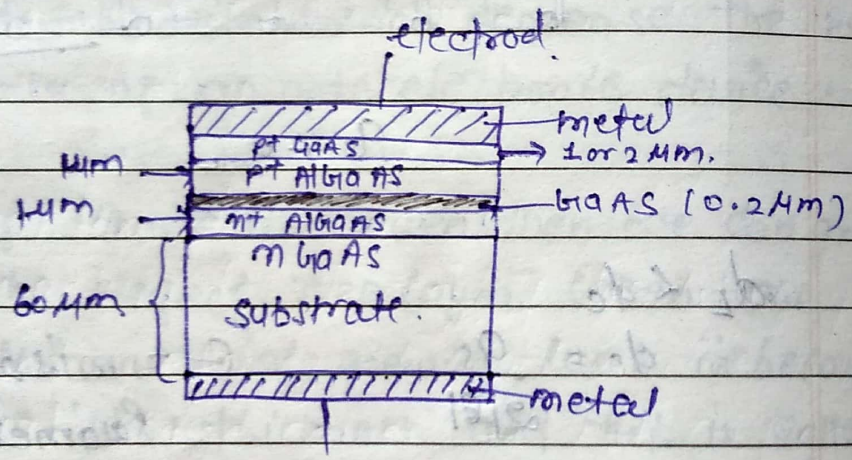
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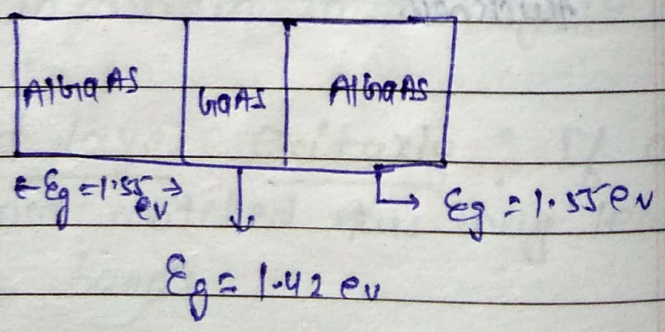
* Quantum well structure :-

Quantum well is a double heterostructure which where thickness of Active layer is real about 100 A°.

Quantum well is a semiconductor double Heterostructure where the thickness of Active layer is always less then the de-Broglie wavelength of the material

Formation / Construction of quantum well structure

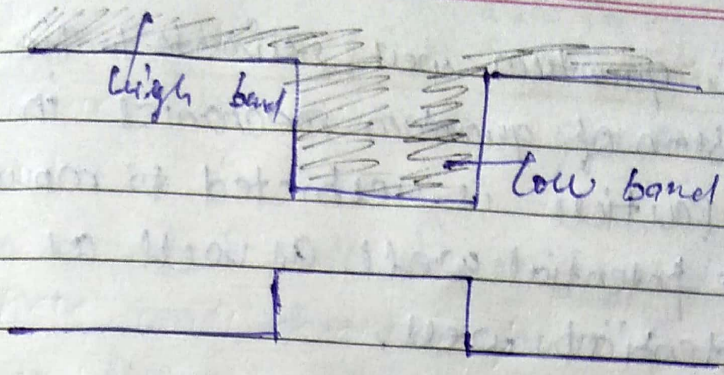




Active band structure

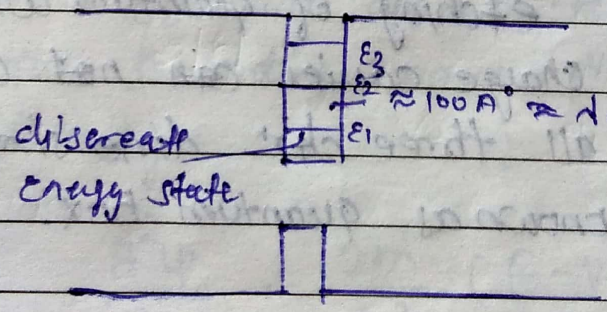
Active region

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- This is a double hetro structure it will not be a quantum well. bez the size of well is not of the order of the de-Broglie wavelength and c.b has continuous energy states.

- If in structure layer epitaxy thickness of the layer is near about 100 A° which is nearly equal to de-broglie wavelength the the quantum effect will take place and the formation of discreate energy levels formed in the c.b



Quantum well.

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This quantum well resimble to the potential well problem of quantum mechanics in which the particle is restricted to move in an finite potential well as well as infinite potential well.

* Quantum wire structure / 1D structure:
quantum wire formed from the quantum well in which a layer pattern with photolithography or $e^{\ominus}$ beam lithography and then etched from the quantum well. Now charge carriers are confined along the two axes one as in quantum well and other dirn depending on the dirn of lithography.

* quantum dot structure:
quantum dot formed if the lithography and etching of quantum wire such that charge carriers not confined in all three dirn. dimensions. it is also known as quantum box.

⇒ that particle (e^-) motion is restricted along x dir^n or dimention of src along x dir in nm range.

as now quantum effect take place then the Schrodinger wave eq^4 in 1D for e^- is given by

$$\frac{d^2\psi}{dx^2} + \frac{2m}{\hbar^2}(E - V)\psi = 0$$

→ ∂

$V(x)$

$\psi(x)$.

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$$\frac{\partial^2\psi}{\partial x^2} \longrightarrow \frac{d^2(\psi)}{dx^2} + \frac{2mE}{\hbar^2}\psi = 0$$

$$\frac{2mE}{\hbar^2} = k^2$$

& k by solving the sch^r eq^n.

$$k = \frac{n\pi}{l}$$

$$\frac{2mE}{\hbar^2} = \frac{n^2\pi^2}{l^2}$$

$$E_n = \frac{n^2\pi^2\hbar^2}{2m^*l^2} \quad \text{or}$$

$$E_n = \frac{n^2h^2}{8m^*l^2}$$

$$\psi = \sqrt{\frac{2}{l}}\left(\frac{n\pi}{l}\right)x.$$

m^* = effective mass of electron.
$n \Rightarrow$ Principle quantum no.
$n = 1, 2, 3 - - -$

* Energy state of $e^\ominus$ in a s/c in 1D or in quantum wire

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$V = 0 \quad 0 < x < L, \; 0 < y < L$

$V = \infty \quad$ elsewhere

$V(x, y) \quad \psi(x, y)$

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + \frac{2m}{\hbar^2}[E - V]\psi = 0$$

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + \frac{2m}{\hbar^2} E\psi = 0$$

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{2m}{\hbar^2} E_x \psi = 0$$

$$\frac{\partial^2 \psi}{\partial y^2} + \frac{2m}{\hbar^2} E_y \psi = 0$$

then the eigen value or energy value of $e^{\ominus}$

$$E = E_x + E_y$$

$$E_x = \frac{n_x^2 h^2}{8ml_x^2} + \frac{n_y^2 h^2}{8ml_y^2}$$

$$= \frac{h^2}{8m}\left[\frac{n_x^2}{l_x^2} + \frac{n_y^2}{l_y^2}\right]$$

two quantum no. n_x and n_y

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$$\psi(x,y) = \psi(x) \cdot \psi(y)$$

$$\psi = \sqrt{\frac{2}{l_x}} \sin\left(\frac{n_x \pi}{l_x}\right) x \cdot \sqrt{\frac{2}{l_y}} \sin\left(\frac{n_y \pi}{l_y}\right) y$$

* Energy state of $e^{\ominus}$ in a s/c in 0D or quantum dot :

$V = 0 \quad 0 < x < l_x, \; 0 < y < l_y, \; 0 < z < l_z$

$V = \infty$ elsewhere

$$\frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial y^2} + \frac{\partial^2\psi}{\partial z^2} + \frac{2m}{\hbar^2}[E - V]\psi = 0$$

$$\frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial y^2} + \frac{\partial^2\psi}{\partial z^2} + \frac{2m}{\hbar^2} E\psi = 0$$

$$\frac{\partial^2\psi}{\partial x^2} + \frac{2m}{\hbar^2} E_x\psi = 0$$

$$\frac{\partial^2\psi}{\partial y^2} + \frac{2m}{\hbar^2} E_y\psi = 0$$

$$\frac{\partial^2\psi}{\partial z^2} + \frac{2m}{\hbar^2} E_z\psi = 0$$

$$E = E_x + E_y + E_z$$

$$\psi = \psi(x) \cdot \psi(y) \cdot \psi(z)$$

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$$E = E_x + E_y + E_z$$

$$= \frac{n_x^2 h^2}{8ml_x^2} + \frac{n_y^2 h^2}{8ml_y^2} + \frac{n_z^2 h^2}{8ml_z^2}$$

$$E = \frac{8h^2}{8m}\left[\frac{n_x^2}{l_x^2} + \frac{n_y^2}{l_y^2} + \frac{n_z^2}{l_z^2}\right]$$

~~two quan~~ three quantum no. n_x & n_y, n_z.

$$\psi(x,y,z) = \psi(x) \cdot \psi(y)\,\psi(z)$$

$$\psi(x,y,z) = \sqrt{\frac{2}{l_x}}\sqrt{\frac{2}{l_y}}\sqrt{\frac{2}{l_z}} \sin\left(\frac{n_x \pi}{l_n}\right)x \cdot \sin\left(\frac{n_y \pi}{l_y}\right)y \sin\left(\frac{n_z \pi}{l_n}\right)z.$$

* Density of states in 3D :- (S)
Density of State (J) in 3D

DOS_{3D} = no. of state Per unit Energy Per unit volume

$$= \frac{1}{V}\frac{dN}{dE}$$

$$= \frac{1}{V} \cdot \frac{dN}{dk} \cdot \frac{dk}{dE} \quad \text{— (1)}$$

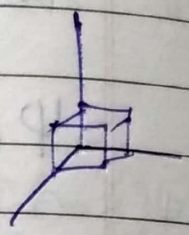
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as N = no. of states in a given k space between energy state E & E+dE

$$N = \frac{2 \times \frac{1}{8} \times \frac{4}{3} \times \pi \times k^3}{(\pi/a)^3}$$

$$= \frac{k^3 a^3}{3 \pi^2}$$



$$= \frac{k^3 a^3}{3\pi^2}$$

$$N = \frac{k^3 a^3}{3\pi^2}$$

$$\frac{dN}{dk} = \frac{a^3 k^2}{\pi^2} \quad \text{(2)}$$

$$k^2 = \frac{2mE}{\hbar^2}$$

$$k\, dk = \frac{2m\, dE}{\hbar^2}$$

$$dE = \frac{\hbar^2}{m} \frac{dE}{k}$$

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$$\frac{dk}{dE} = \frac{m}{\hbar^2} \cdot \frac{1}{k} \quad - (3)$$

$$DOS_{3D} = \frac{1}{V} \frac{a^3 k^2}{\pi^2} \times \frac{m}{\hbar^2} \cdot \frac{1}{k}$$

Volume is taken physical volume

$$V = a^3$$

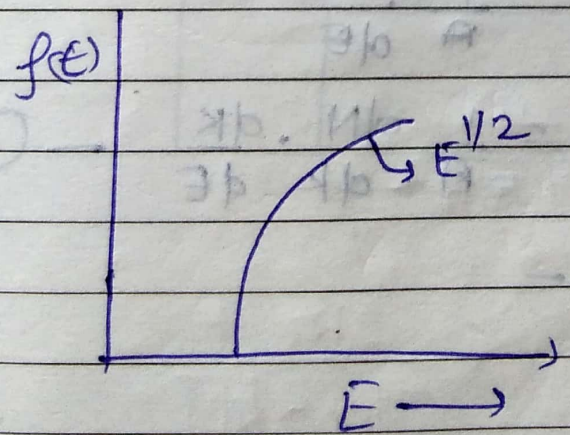
$$DOS_{3D} = \frac{1}{a^3} \cdot \frac{a^3 k^2}{\pi^2} \times \frac{m}{\hbar^2} \cdot k$$

$$= \frac{k}{\pi^2 \hbar^2} m.$$

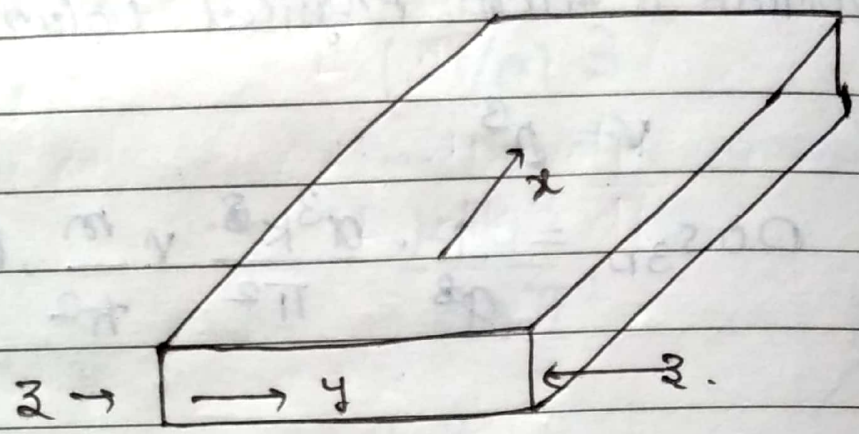
$$\boxed{DOS_{3D} = \frac{m^{*3/2} 2^{1/2} E^{1/2}}{\pi^2 \hbar^3}}$$

$$DOS \propto E^{1/2}$$

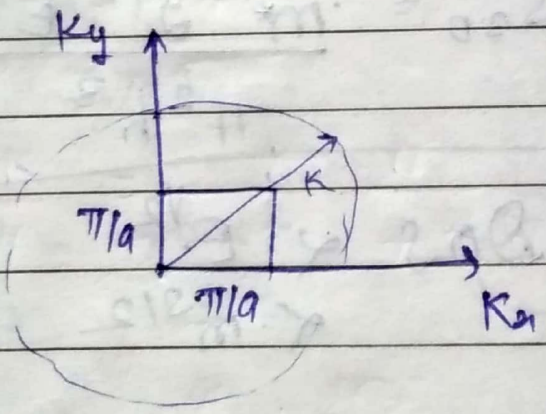
$$\propto m^{3/2}$$



the one direction (z direction) and moves freely along x and y axis's (quantum well)



moving of $e^{\ominus}$ → x, y
confined along → z.



$$DOS_{2D} \Rightarrow \frac{1}{A}\frac{dN}{dE}$$

$$= \frac{1}{A}\frac{dN}{dk}\cdot\frac{dk}{dE} \quad \text{— (1)}$$

=

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$$N = \frac{\frac{2}{4} \times \pi k^2}{(\pi/a)^2} = \frac{a^2 k^2}{2\pi}$$

$$\frac{dN}{dk} = \frac{a^2 k}{\pi} \quad \text{— (2)}$$

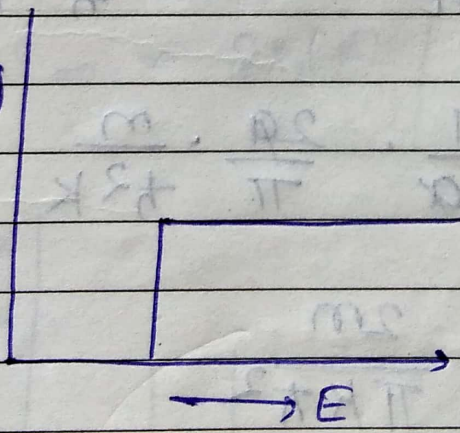
$$\frac{dk}{dE} = \frac{m}{\hbar^2 k} \quad \text{— (3)}$$

$A = a^2$

$$DOS_{2D} = \frac{1}{a^2} \cdot \frac{a^2 k}{\pi} \cdot \frac{m}{\hbar^2 k}$$

$$\boxed{DOS_{2D} = \frac{m^*}{\pi \hbar^2}}$$

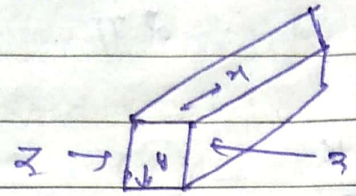
DOS_{2D} is independent of energy.



Dated :

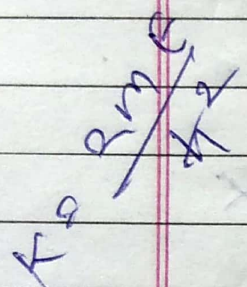
Page :

* Density of State in 1D / quantum wire



$$DOS_{1D} = \frac{1}{L}\frac{dN}{dE}$$

$$= \frac{1}{L}\frac{dN}{dk}\cdot\frac{dk}{dE}$$



$$N = \frac{2\pi k}{\pi/a}$$

$$N = \frac{2\pi k a}{\pi}$$

$$\frac{dN}{dk} = \frac{2a}{\pi}$$

$$\frac{dk}{dE} = \frac{m}{\hbar^2 k}$$

$$= \frac{1}{a}\cdot\frac{2a}{\pi}\cdot\frac{m}{\hbar^2 k}$$

$$DOS_{1D} = \frac{2m}{\pi k \hbar^2}$$

$$DOS_{1D} = \frac{2m}{\pi \hbar^2 \sqrt{2mE}}$$

factorization of mm

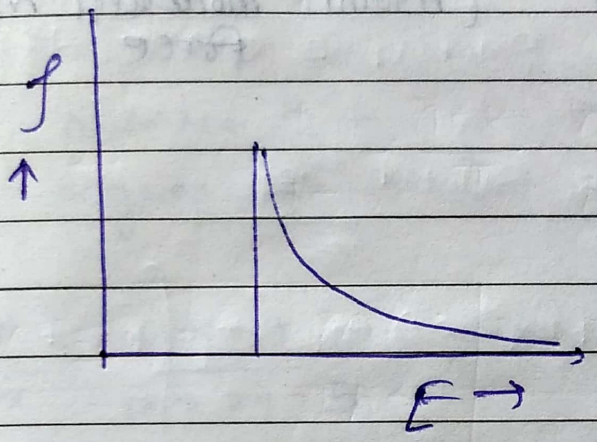
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Page :

$$DOS_{1D} = \frac{2m^*}{\pi \hbar^2 \sqrt{2mE}}$$

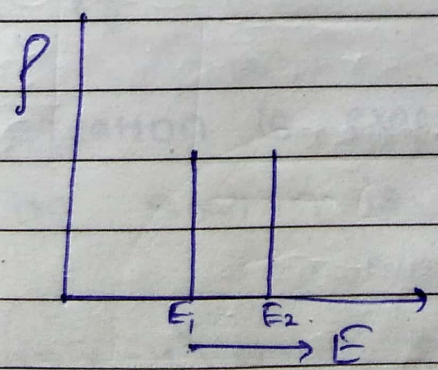
$$\boxed{DOS_{1D} = \frac{(2m^*)^{1/2} E^{-1/2}}{\pi \hbar}}$$

$$DOS \propto E^{-1/2}$$



* Density of state in 0D :

$$\boxed{DOS_{0D} = 2 \times \delta E}$$



Dated :
Page :

* Characterization of nanostructure or low dimension material can be done by following instruments or techniques.

(1) XRD (X-Ray defrectometer)
(2) SEM (Scanning effect microscopy)
(3) TEM (Tunneling effect microscopy)
(4) AFM (Atomic force microscopy)